PHYSICAL AND MECHANICAL PROPERTY VARIATION OF BLACK ASH (*FRAXINUS NIGRA* M.) GROWN IN THE THUNDER BAY SEED ZONE

by

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Keywords: *Fraxinus nigra* Marsh., mechanical properties, longitudinal variation, radial variation, wood properties mapping, juvenile wood, mature wood.

The identification of traditionally underutilized species with the potential for development and increased marketing potential has been recognized as a source of potential innovation in the Northwestern Ontario forest sector. However, the industry requires improved knowledge of the physical and mechanical properties of these species and how this information can be applied to end use attributes in value added forest products. Black ash (*Fraxinus nigra* Marsh.) is abundant throughout the region, yet has been identified as an underutilized species with limited available literature on properties or potential variations. Nine mature black ash trees from the Thunder Bay Seed Zone were destructively sampled and wood properties in differing radial and longitudinal positions were measured and recorded. Longitudinal positions reflect 0, 25, 50 and 75 percent of total merchantable height. Radial positions reflect the juvenile wood core, transition zone and mature wood of each stem. Measured wood properties include MOE, MOR, compression parallel to the grain, Janka ball side hardness, relative density, ring width, latewood percentage and average ring density. Results indicate stable and predictable wood properties in the radial direction with only percentage of latewood varying significantly radially. Longitudinal position reflected increased variance with MOE, compression parallel to the grain, side hardness and ring width displaying significant results. The greatest level of variability was observed between sites in each of the selected properties. Results consistently displayed two subsets of sites; reflecting the second and third sites, or three distinct sites. Increased mechanical property values were identified in the upland and well-drained sites as compared to the lowland site. In the future, benefits exist for increased processing potential, as inherent properties are consistent throughout the tree including the desirable heartwood section. It was determined that site conditions play a significant role in the inherent wood properties and opportunities exist for forest managers to predict mechanical properties based on site characteristics.

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INTRODUCTION

The Ontario forest sector is a vital component of the Canadian economy, contributing over 12 billion annually to the economy (Auditor General of Ontario, 2011). Many communities rely heavily on forest sector employment with an estimated 166,000 Ontarians employed directly within the industry (Auditor General of Ontario, 2011). However, severe external pressures have created challenging times for the industry and resulted in serious decline over the past decade. The Canadian Council of Forest Ministers (CCFM) (2008) and the Auditor General of Ontario (2012) summarize these pressures, which include;

- Appreciation of the Canadian dollar
- Economic recession in the United States
- Rising input costs
- Increasing global competition
- New, lower cost competitors in the marketplace

In order to remain relevant and competitive on a global scale, the forest industry has been forced to undergo long term transformations and adjustments. There has been a push towards a knowledge economy, focused on innovation, research and product development (CCFM, 2008). New opportunities throughout the value chain are necessary, with a focus on untapped resources and potential (CCFM, 2008).

Broadly, the goal of this thesis was to examine these transformations in the context of Northwestern Ontario. Mainly, how can the region become more competitive, focus on new applications and develop a vast wood supply.

Underutilized species were identified in the region with the potential for increased development and marketing potential. The Ontario Ministry of Natural Resources (OMNR) (2007) recognizes 12 species as common or abundant in Northwestern Ontario. Much utilization and research has focused on the desirable softwood species, *Picea mariana* (Mill.) BSP, *Picea glauca* (Moench) Voss and *Pinus banksiana* Lamb., however, much less attention has been directed towards hardwoods species (Cutter *et al.,* 2004; Evans *et al.,* 2000; Harrington and DeBell, 1980; Methven, 1982; O'Keefe, 1982; OMNR, 2007). Further research in recent years has been devoted to species deemed underutilized, including; *Thuja occidentalis* L., *Larix laricina* (Du Roi) K. Koch and *Betula papyrifera* Marsh.

Black ash (*Fraxinus nigra* Marsh.) is another species considered underutilized and little information is available regarding its properties and characteristics (Alden, 1994; Cassens, 2007; Panshin and de Zeeuw, 1980; Wright and Rauscher, 1990). However, the species is abundant across Ontario and the Lake States and is commonly found in the Southern portions of Northwestern Ontario (OMNR, 2007; Wright and Rauscher, 1990). In total it represents approximately 20 million cubic metres of growing stock in Ontario (OMNR, 2007). Utilization of black ash in Northwestern Ontario is currently limited and results in wasted resources and a lack of production potential. However, Alden (1994) notes that the wood ranks favourably when compared to other native hardwoods, is inexpensive and largely underutilized.

The main objective focused on understanding the variation in physical and mechanical properties in both the radial and longitudinal direction. An understanding of these variations would allow the forest industry to better understand properties of black ash found in the region with the goal of improving product quality and utilization potential. The need for such research in underutilized species has been noted extensively within the literature (Adamopoulos, 2007;

Carmean and Boyce, 1973; Evans *et al.,* 1998; Jett and Zobel, 1975; Kellogg, 1982; Koga and Zhang, 2004; Maeglin, 1976; Okkonen *et al.,* 1971; Park *et al.,* 2009; Stringer and Olson, 1987; Van Buijtenen, 1969; Zhang *et al.,* 1994; Zobel and van Buijtenen, 1989; Zobel, 1964). Hamilton (1961) noted that many species are underutilized given the lack of specific knowledge on their attributes.

It was hypothesized that physical and mechanical properties would vary considerably given that it has been widely documented that properties vary within a tree in three distinct ways; within a growth ring, radially from pith to bark, and longitudinally from stump to crown (Koga and Zhang, 2004; Panshin and deZeeuw, 1980; Zobel and van Buijtenen, 1989).

Mechanical property tests were performed on small clear samples utilizing Tinius Olsen H10KT and H50KT Universal Wood Testing Machines, complete with Test Navigator software. Samples utilized for mechanical tests were also utilized in relative density determination. Analysis of variance (ANOVA) was utilized to determine the significance of variation in both the radial and longitudinal direction and when appropriate, Duncan's post hoc test was used to determine statistically similar values. Finally, the relationship between relative density and mechanical properties was investigated using linear, logarithmic and exponential equations.

This thesis is organized into six main chapters. Chapter two reviews the available literature related to tree growth, wood formation and structure, as well as an introduction to physical and mechanical properties and their known variations. Further, black ash characteristics and utilization are discussed. The third chapter describes methodology related to data collection in the field and laboratory, as well as statistical analysis. Chapter four presents the results and summaries of the radial and longitudinal variation within the sample data. Major results and findings are discussed in chapter five, while chapter six concludes with implications for utilization and future research.

LITERATURE REVIEW

TREE GROWTH, WOOD FORMATION AND WOOD STRUCTURE

A complete understanding of tree growth, wood formation and wood structure is a vital component in further understanding mechanical properties and the eventual end utilization of wood products. Genetic factors dictate much of the growth responses within trees, accounting for the trees reaction to varying environmental conditions (Wilson, 1984). However, less is understood in regards to how site conditions affect growth. It is assumed that wood growth is highly variable and differs considerably within trees, within species and between species (Zobel and van Buijtenen, 1989).

The complex process of photosynthesis within a tree creates the necessary resources for growth (Bowyer *et al.,* 2003; Wilson, 1984). These resources are utilized first in the root and shoot apical meristems, followed by diameter growth in the lateral meristems (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980; Panshin and de Zeeuw, 1980).

Root and Shoot Apical Meristems

Height and root growth within trees, also known as elongation, occurs in specialized zones within the tip of the main stem, roots, and shoots. These zones are known as apical meristems (Bowyer *et al*, 2003; Tsoumis, 1991; Wilson, 1984). Specialized reproducing cells within the meristems rapidly divide to produce new tissue. These new tissue cells follow a distinct longitudinal order, stacked one on top of another, resulting in the typical elongation of stems and shoots (Bowyer *et al.,* 2003). As new tissue is produced, the meristematic cells are pushed outwards, leaving behind the most recently produced cells (Bowyer *et al.,* 2003; Keith and Kellogg, 1981; Panshin and de Zeeuw, 1980; Wilson, 1984).

Little is understood regarding the variation in height of different species of trees. It is assumed that trees will grow tall when resources are abundant and stress is low (Koch *et al.,* 2004). However, trees have developed an evolutionary balance in regards to the costs and benefits of height growth (King, 1990). These genetic controls are coupled with the ever-changing constraints placed on the tree under varying site conditions (King, 1990; Koch *et al.,* 2004; Wilson, 1984).

Lateral Meristems

Wood formation in trees occurs within the vascular cambium, a thin, lateral meristem that produces xylem (wood) and phloem (bark) to its inside and outside, respectively (Bowyer *et al.,* 2003; Keith and Kellogg, 1981; Larson, 1994; Tsoumis, 1991). This growth increases the diameter of the tree outward and the constant cell division within the cambium allows trees to produce wood with varying physical properties throughout the life of the tree (Keith and Kellogg, 1981; Larson, 1962; Larson, 1994; Panshin and de Zeeuw, 1980).

The division of the cambium cells commences in the spring and ceases shortly afterwards (Bowyer *et al.,* 2003; Jozsa and Middleton, 1994; Larson, 1962; Larson, 1994). However, cambial cell differentiation continues throughout the process of shoot elongation, at which point the production of latewood begins and continues until differentiation ceases in late summer or early fall (Fries and Ericsson, 2008; Jozsa and Middleton, 1994; Larson, 1960; Larson, 1994; Tsoumis, 1991). This pattern of growth is reflected in the annual growth rings of trees found in temperate zones within the Northern Hemisphere (Desch and Dinwoodie, 1996; Keith and Kellogg, 198; Larson, 1962; Panshin and de Zeeuw, 1980; Wilson, 1984). Within these trees, wood formed earliest in the growing season is known as earlywood and is characterized by thin cell walls and larger lumen spaces (Figure 1). The wood produced later in the season is known as latewood and is characterized by smaller cells, composed of thicker walls and smaller lumen spaces (Figure 1) (Desch and Dinwoodie, 1996; Fries and Ericsson 2008; Jane, 1956; Jozsa and Middleton, 1994; Keith and Kellogg 1981; Panshin and de Zeeuw, 1980).

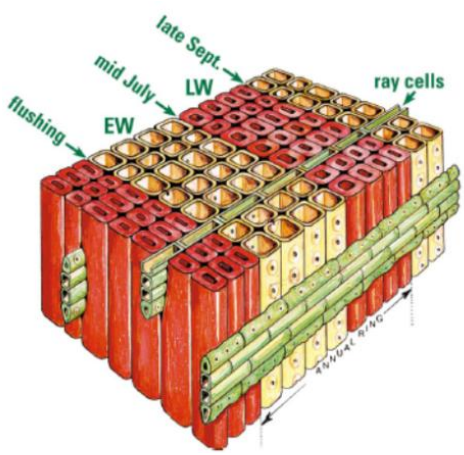

Figure 1. Structure and arrangement of earlywood and latewood cells within a growth ring (Jozsa 1999).

Kennedy (1961) noted that the timing of the transition from earlywood to latewood varies within individual trees and suggests that genetics is partially responsible (Fries and Ericsson, 2008). Gilmore *et al.,* (1966) suggested moisture availability is a common environmental factor associated with the change from earlywood to latewood (Bowyer *et al.,* 2003; Zobel and van Buijtenen, 1989).

The transition from earlywood to latewood within a ring can be gradual or abrupt. However, Larson (1960) noted that regardless of transition type, a zone of intermediate wood forms between the earlywood and latewood, which can be defined as neither wood (Fries and Ericsson, 2008; Zobel and van Buijtenen, 1989). Regardless of timing, in ring porous woods, the percentage of earlywood remains consistent within the ring, while, the percentage of latewood within the ring can vary considerably from year to year, largely as a result of growth rate (Panshin and de Zeeuw, 1980). Thus, in ring porous woods, smaller ring widths within the tree result in smaller percentages of latewood (Panshin and de Zeeuw, 1980; Tsoumis, 1991; Zobel and van Buijtenen, 1989). An opposite pattern is observed in softwoods where the percentage of latewood remains fairly consistent regardless of growth rate, while the earlywood percentage increases with a faster growth rate (Panshin and de Zeeuw, 1980).

The width of the annual growth rings varies in response to the position of the tree within the stand (Jozsa and Middleton, 1994; Tsoumis, 1991). Open grown trees with numerous branches or those with very large crowns often increase ring width from the crown to the base of the tree. Suppressed trees may actually cease cambial activity near the base of the tree (Larson, 1960; Wilson, 1984).

Ring width also varies based on the position of the ring in relation to the crown of the tree (Jozsa and Middleton, 1994; Larson, 1962; Wilson, 1984). Under normal forest grown conditions, the ring most recently formed is smallest near the top of the tree and gradually increases in width to its widest point at the base of the crown, where the most productive branches exist (Tsoumis, 1991). There is then a gradual decrease in width towards the stump of the tree where an increase in width typically occurs in relation to the presence of large lateral roots (Panshin and de Zeeuw, 1980; Tsoumis, 1991; Wilson, 1984).

The above variations in ring width are largely a result of the flow of available resources within the tree (Jozsa and Middleton, 1994; Larson, 1994; Tsoumis, 1991). Panshin and de Zeeuw (1980) and Larson (1956) suggest two related theories to explain the flow of resources within a tree. The nutritional theory suggests that food material originating in the crown is utilized rapidly in the upper sections of the tree with decreasing amounts available to lower sections. Larson (1956) suggests that the delayed arrival or complete lack of growth hormones within the tree can result in a lack of differentiation within the cambium. Thus, variation in ring width results from cambial activity initiating within the crown in the spring and moving rapidly down the stem (Figure 2) (Panshin and de Zeeuw, 1980; Tsoumis, 1991).

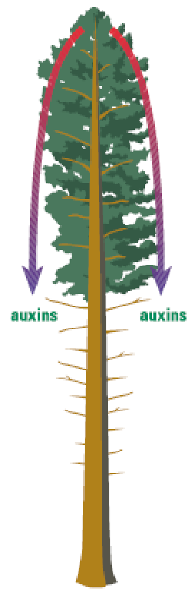

Figure 2. Pattern of initiation of cambial activity (Jozsa, 1999).

WOOD STRUCTURE

Tree species found in North America are classified into two categories: conifer trees, also known as softwoods or evergreens and deciduous trees, also known as hardwoods or broadleaves (Panshin and de Zeeuw, 1980). These two categories of trees are distinguished by changes in physical properties resulting from differences in cell structure and composition within the tree (Keith and Kellogg, 1981).

A hardwood tree possesses a complex and intricate makeup of cells that vary considerably in size, shape and arrangement within the tree (Bowyer *et al.,* 2003; Jane, 1956; Keith and Kellogg, 1981). It is thought that hardwoods evolved later than softwoods and developed more specialized cell types specific to necessary functions in the tree (Fukazawa, 1984; Hoadley, 2000; Jane, 1956; Koehler, 1933; Wilson and White, 1986).

Hardwoods are composed of four main cell types; vessels, fibres, parenchyma, and ray cells (Bowyer *et al.,* 2003; Cown and Parker, 1978; Jane, 1956; Panshin and de Zeeuw, 1980). Two forms of tracheids are also found in small amounts within ring porous hardwood trees, namely vasicentric and vascular (Hoadley, 1990; Jane, 1956; Panshin and de Zeeuw, 1980).

The most recognizable feature of hardwood trees is the presence of vessel elements or pores, which are tube-like structures of short length and large diameter (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980). Hardwood trees can be classified into three distinct categories based on the variation in size and location of the vessel elements within a growth ring (Hoadley, 1990; Jane, 1956; Keith and Kellogg, 1981; Panshin and de Zeeuw, 1980).

When vessel elements are of uniform size and even distribution throughout the early and latewood, the species is described as diffuse porous (Bowyer *et al.,* 2003; Hoadley, 2000). Examples of diffuse porous species include *Betula spp., Acer spp. and Tilia spp.* (Hoadley, 2000; Panshin and de Zeeuw, 1980; Tsoumis, 1991). *Fraxinus spp., Quercus spp*., and associate species are classified as ring porous, as the vessels formed earlier in the season are much larger than those formed later in the year (Figure 3) (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996, 1981; Hoadley, 2000; Panshin and de Zeeuw, 1980; Tsoumis, 1991). In some species, the vessel elements are larger in the earlywood and grade to a smaller size in the latewood but contain no clear pattern or zoning. These species are known as semi-diffuse porous and include *Juglans nigra* L. and *Juglans cinerea* L. (Hoadley, 2000; Panshin and de Zeeuw, 1980; Tsoumis, 1991).

Vessels elements appear within the ring as solitary elements or grouped together in a number of ways (Desch and Dinwoodie, 1996; Jane, 1956; Panshin and de Zeeuw, 1980). This variation in vessel elements is characteristic of individual species and a distinct clue towards species identification (Hoadley, 1990; Keith and Kellogg, 1981).

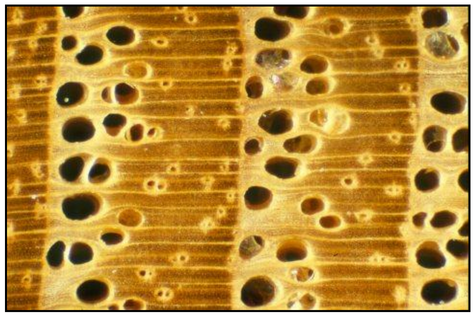

Figure 3. Anatomy of black ash displaying large early wood pores (Hoadley, 1990).

Fibres are frequently described incorrectly within the literature and utilized as a loose terminology to describe all wood cells (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980). However, fibres are defined as long, narrow cells with closed ends and thick walls found in all hardwoods (Bowyer *et al.,* 2003; Keith and Kellogg, 1981; Panshin and de Zeeuw, 1980).

Two types of fibres are present in hardwoods; fibre tracheids and libriform fibres and are distinguished based on the nature of the pitting in the cell walls (Hoadley, 1990; Jane, 1956; Tsoumis, 1991). Both types of fibres vary greatly in diameter, length, thickness of cell wall and total volume (Tsoumis, 1991). This variation exists not only between species but also between individual trees and even within individual sections of a tree (Keith and Kellogg, 1981; Panshin and de Zeeuw, 1980).

Parenchyma are short, thin walled cells tasked with the job of storing and distributing carbohydrates within the tree (Bowyer *et al.,* 2003; Jane, 1956; Panshin and de Zeeuw, 1980). There are three distinct forms of parenchyma found in hardwoods; strand parenchyma, fusiform parenchyma and epethial parenchyma (Hoadley, 1990; Panshin and de Zeeuw, 1980). Parenchyma cells are distributed within the tree in various ways dependent on the type of parenchyma and species of tree. They can occur as strands along the grain and can be seen as dots, sheaths surrounding pores or continuous bands (Panshin and de Zeeuw, 1980; Tsoumis, 1991).

Parenchyma are also the primary cells found within rays (Keith and Kellogg 1981; Panshin and de Zeeuw, 1980). These ray parenchyma cells can be either upright parenchyma or procumbent parenchyma, oriented with their long axis vertically or horizontally, respectively (Bowyer *et al.,* 2003; Tsoumis, 1991).

Two distinct types of tracheids are found within certain hardwoods: vascular tracheids and vasicentric tracheids (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980). Vascular tracheids are similar in size and shape to vessel elements found in the latewood and are associated with the latewood vessels of certain ring porous species (Bowyer *et al.,* 2003; Tsoumis, 1991). However, vascular tracheids lack the large perforated openings at the cells ends as found in vessel elements and instead are composed of walls lined with many intervessel pits, with non-perforated tapering ends (Bowyer *et al.,* 2003; Hoadley, 1990; Panshin and de Zeeuw, 1980). Vascular tracheids arrange themselves in similar vertical arrangements as vessels and often are intermixed in no particular arrangement (Panshin and de Zeeuw, 1980).

Ring porous woods contain short, irregularly shaped cells with closed ends known as vasicentric tracheids (Hoadley, 1990; Tsoumis, 1991). These tracheids are abundant in close proximity to the large earlywood vessels (Hoadley, 1990; Panshin and de Zeeuw, 1980; Tsoumis, 1991). In both cases, the tracheids can be found in association with the axial vessels (Panshin and de Zeeuw, 1980).

The relative proportions of each cell type can vary distinctly within each species (Koehler, 1933; Panshin and de Zeeuw, 1980). Table 1 displays the average volumetric composition of cell types in black ash and other ring porous hardwood species. Fibres constitute nearly 70 percent of the total cell volume in black ash and thus are largely responsible for the given characteristics of the species (Desch and Dinwoodie, 1996; Koehler, 1933; Panshin and de Zeeuw, 1980). However, the smaller amounts of axial parenchyma, ray cells and large void space found within the vessels elements will also have an effect on characteristics (Cown and Parker, 1978; Keith and Kellogg, 1981; Panshin and de Zeeuw, 1980). Percentages of vasicentric and vascular tracheids are not included in the table as this cell type is variable in its presence and is not typically measured.

Table 1. Average volumetric composition of black ash and associated species.

	Percentages of Total Volume			
Species	Vessels	Fibres	Rays	Axial Parenchyma
Fraxinus nigra	11.6	69.4	12.0	7.0
Fraxinus americana	20.4	61.7	11.9	4.2
Quercus rubra	21.6	43.5	21.4	13.5
Ulmus americana	48.0	34.7	11.3	6.0

Source: (Panshin and de Zeeuw, 1980)

CHEMICAL COMPONENTS

Wood is composed of structural cellulose, hemicelluloses and lignin; which contribute 40 to 50 percent, 20 to 35 percent and 15 to 35 percent of the dry weight of wood, respectively (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1981; Jozsa and Middleton, 1994; Panshin and de Zeeuw, 1980). This is confirmed by Clermont and Schwartz (1952) who studied the chemical components of black ash and determined cellulose to be 47 percent, hemicellulose to be 21 percent and lignin to be 18 percent of the total structure. As nearly half the dry weight of wood is composed of cellulose, it has the largest effect on both volume and characteristics of wood (Bowyer *et al.,* 2003; Jane, 1956; Panshin and de Zeeuw, 1980).

Non-structurally, wood contains large amounts of extraneous materials or extractives; including tannins, volatile oils, resins, gums and dyes; as well as small amounts of ash (Bowyer *et al.,* 2003; Jane, 1956; Panshin and de Zeeuw, 1980). Though these substances are not essential components of wood structure their presence is related to permeability and several physical properties including density (Jane, 1956; Panshin and de Zeeuw, 1980).

The actual amount of extractives found within wood varies considerably between species. Generally, a few percent of the total oven-dry-weight is composed of extractives. However, values as high as 20 to 30 percent have been reported (Panshin and de Zeeuw, 1980; Tsoumis, 1991). Increased weight associated with higher extractive content can lead to increased density values as found by Taras and Saucier (1967) who reported an overestimation of 6.0 to 7.5 percent for specific gravity values for southern *Pinus spp*. when examining un-extracted sample cores. Keith (1969) found similar results in *Pinus resinosa* Ait. showing averages of 0.337 and 0.349 for extracted and un-extracted samples, respectively.

STRUCTURAL COMPONENTS

Structurally, all cells are composed of two distinct layers: a thin primary wall, and a thicker secondary wall with three layers known as S1, S2 and S3 (Figure 4) (Bowyer *et al.,* 2003; Jane, 1956; Panshin and de Zeeuw, 1980). The primary wall forms initially as the outermost cell wall and thickens as it reaches maturity (Desch and Dinwoodie, 1996), followed by the three layers of the secondary wall (Bowyer *et al.,* 2003). These three S-layers are composed of multiple layers known as laminae, which are aligned in distinct orientations to provide structural support within the cell wall. This orientation of laminae is known as the microfibril angle (MFA) (Bowyer *et al.,* 2003; Keith and Kellogg, 1981; Panshin and de Zeeuw, 1980). The S1 and S3 layers are relatively thin and are composed of several laminae at a similar angle to the long axis of the cell (Bowyer *et al.,* 2003). The thick S2 layer comprises the bulk of the cell wall and is composed of multiple laminae, which largely control the physical behaviour of cell material and in mature wood are at angles almost opposite to the S1 and S2 layers (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1981; Keith and Kellogg, 1981). This layer shows the greatest variation in thickness and has a large influence on density and related wood properties (Keith and Kellogg, 1981; Panshin and de Zeeuw, 1980).

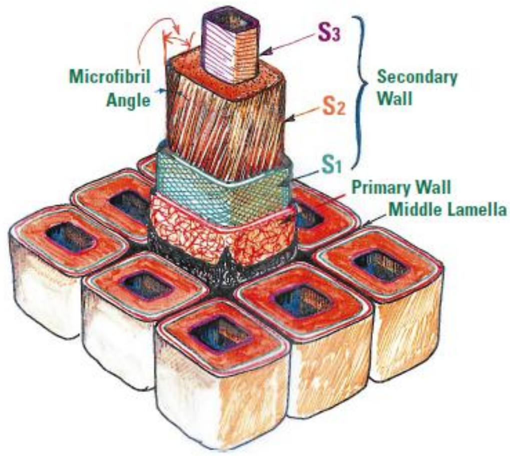

Figure 4. Layers of the cell wall displaying MFA's and relative size (Jozsa, 1999).

JUVENILE WOOD

As a tree matures, the structure and composition of the cells produced by the cambium varies and has effects on the physical and mechanical properties throughout the tree (Figure 5) (Cutter *et al.,* 2004; Hildebrandt, 1960; Maeglin, 1978; Panshin and de Zeeuw, 1980; Phelps and Chen, 1989; Pliura *et al.,* 2006; Sauter *et al.,* 1999; Zhang *et al.,* 1990Zobel and van Buijtenen, 1989).

Mature wood is defined as having properties characteristic of the species under normal conditions. By contrast, juvenile wood is defined by structural characteristics and physical properties, which are different to those of mature wood (Yang *et al.,* 1986; Zobel and van Buijtenen, 1989). When compared to normal or mature wood, juvenile wood is characterized as having;

- Variations in density
- Lower strength properties
- Thinner cell walls
- Shorter fibre lengths
- Larger lumen spaces
- Larger MFA's
- Lower or non-existent true latewood formation
- Larger reaction wood content
- Higher moisture content
- Higher lignin content
- Lower cellulose content
- Increased longitudinal shrinkage
- Increased occurrence of drying defects

(Alteyrac *et al.,* 2006; Evans *et al.,* 2000; Fukazawa, 1984; Jane, 1956; Maeglin, 1978; Yang *et al.,* 1986; Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989)

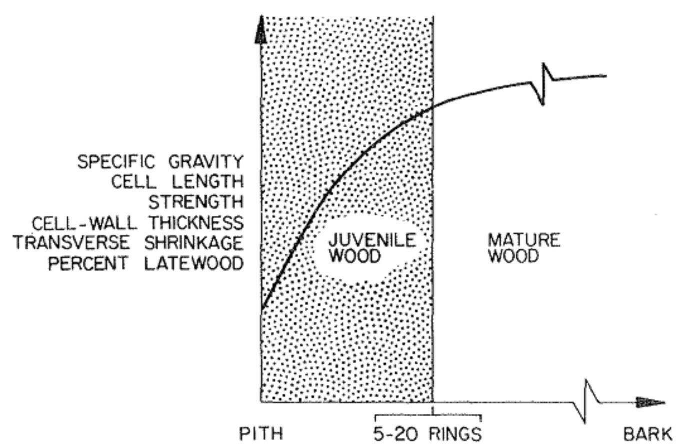

Figure 5. Juvenile to mature wood transition (Bendtsen, 1978).

It was originally believed that juvenile wood was "crown formed wood" due to its high concentration in the crown of a tree (Jozsa and Middleton, 1994; Larson, 1960; Larson, 1962; Larson, 1969; Yang *et al.,* 1986). Although technically accurate, it is now suggested that juvenile wood formation is a result of the age of the cambium (Alteyrac *et al.,* 2006; Fukazawa, 1984; Yang *et al.,* 1986; Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989). That is, juvenile wood is formed by a juvenile or immature cambium whereas mature wood is formed by a mature cambium (Jozsa and Middleton, 1994; Yang *et al.,* 1986; Zobel and Sprague, 1998). Given that the top of the tree always has an immature cambium, juvenile wood is formed extensively in the crown (Larson, 1962; Zobel and Sprague, 1998). While the more mature cambium at the base of the tree forms increasing amounts of mature wood as the distance from the pith increases (Figure 6). This trend persists so long as height growth continues in the crown (Larson, 1962; Yang *et al.,* 1986; Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989).

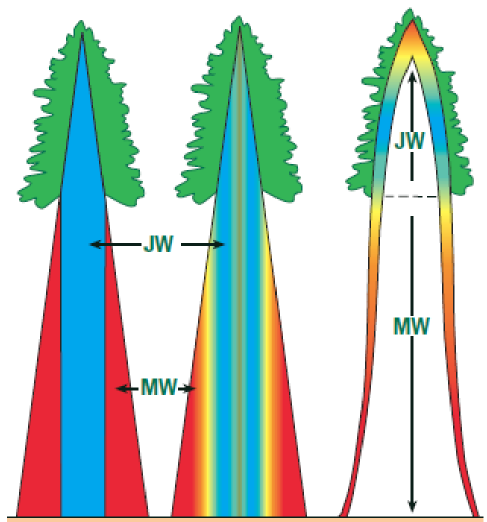

Figure 6. Patterns of juvenile wood within a tree (Jozsa 1999).

The production of juvenile wood is controlled largely by auxins produced in the crown (Figure 2), which suggests an additional cause for the increased amount of juvenile wood in the crown of the tree (Alteyrac *et al.,* 2006; Zobel and van Buijtenen, 1989). Di Luca (1989) and Jozsa and Middleton (1994) concluded that the size and length of the live crown seemed to regulate the proportions of juvenile and mature wood in the stem. However, it has been suggested that other factors including genetics, site conditions, competition, climate, and silvicultural activities can all influence juvenile wood production (Maeglin, 1978; Sauter, 1999; Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989).

The delineation between juvenile and mature wood zones within a tree is not distinct and often occurs over a period of several years (Bowyer *et al.,* 2003; Evans *et al.,* 2000; Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989). Wood characteristics in the juvenile zone are inconsistent and change rapidly from the pith outward (Zobel and Sprague, 1998). This is followed by a transition zone where changes slow and eventually lead to the development of a mature wood zone wherein properties are more consistent (Evans *et al.,* 2000; Zobel and van Buijtenen, 1989). It is believed that juvenile wood extends from 5 to 20 years from the pith, dependant on the species and properties measured (Bowyer *et al.,* 2003; Evans *et al.,* 2000). Zobel and van Buijtenen (1989) noted that the top sections of a mature tree may be composed entirely of juvenile wood and this is certainly true of stem sections above the merchantable top. However, the proportion of juvenile wood found throughout the tree decreases rapidly with increasing age of the tree (Zobel and Sprague, 1998). Saucier (1987) noted that juvenile wood as a percentage of total tree volume is about 50 percent at 22, 30 percent at age 32 and 20 percent at age 40 (Zobel and van Buijtenen, 1989).

The impact of juvenile wood in hardwoods is far less pronounced than in softwoods, owing largely to the fact that the density of juvenile wood in hardwoods is typically only slightly different than that of mature wood (Evans *et al.,* 2000; Maeglin, 1978; Tsoumis, 1991; Zobel and Sprague, 1998). This results in a more homogenous wood in both the radial and longitudinal direction (Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989). For this reason, the variation and effects of juvenile wood in hardwoods has largely been ignored within the scientific literature (Evans *et al.,* 2000; Tsoumis, 1991; Zobel and van Buijtenen 1989). This is particularly true of black ash and associate species where little evidence exists as to the degree of change from juvenile to mature wood.

TENSION WOOD

Hardwood trees produce a special form of reaction wood known as tension wood that corrects lean and maintains proper branch orientation (Desch and Dinwoodie, 1996; Jane, 1956; Maeglin, 1978). Tension wood occurs on the upper side of a branch and the upper-side of a leaning main stem (Figure 7) (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1981; Jane, 1956; Maeglin, 1978).

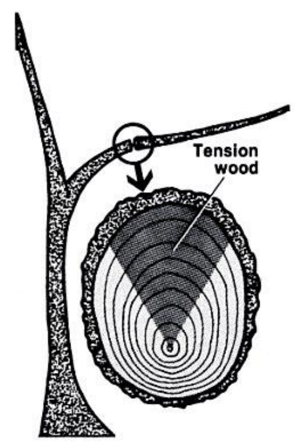

Figure 7. Larger, elliptical shaped rings found in tension wood (Desch and Dinwoodie, 1996).

Tension wood has unique characteristics that make it distinctly different from that of normal wood (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980; Tsoumis, 1991; Wilson and

White, 1986). The vessels, rays and parenchyma of tension wood are smaller and less numerous than in normal wood (Panshin and de Zeeuw, 1980; Tsoumis, 1991). Tension wood also contains a greater percentage of fibres than found in normal wood. These fibres are smaller in diameter, greater in length and contain fewer pits (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980). Chemically, tension wood is characterized as having severely reduced lignification in the cell wall (Bowyer *et al.,* 2003; Tsoumis, 1991). This is contrasted by increased amounts of cellulose, as much as 40 to 50 percent over amounts found in normal wood (Panshin and de Zeeuw, 1980; White and Robards, 1965; Zobel and van Buijtenen, 1989).

In addition to cell distribution and chemical composition, the principle distinction between tension wood and normal wood is the modification of the structure and formation of fibres (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980; Zobel and van Buijtenen, 1989). Tension wood fibres develop a distinct layer of microfibrils, which replace the S3 layer, known as the gelatinous layer (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Panshin and de Zeeuw, 1980; White and Robards, 1965; Wilson and White, 1986; Zobel and van Buijtenen, 1989). This sheath of microfibrils, which always appears on the lumen side of the cell wall, can be equal to or greater in thickness than the *S*2 layer of a normal cell wall (Tsoumis, 1991). The gelatinous layer may be produced in addition to the normal cell walls or may replace one or both of the *S*2 and *S*3 layers (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980; White and Robards, 1965; Wilson and White, 1986; Zobel and van Buijtenen, 1989). It is also common for the gelatinous layer to delaminate from the S2 layer (Koehler, 1933; Jane, 1956; Tsoumis, 1991; White and Robards, 1965).

The differences in structure and anatomical characteristics between normal wood and tension wood results in a variation in properties throughout the stem (Zobel and van Buijtenen, 1989). Tension wood has a higher density than normal wood as a result of the thicker and longer fibres found in the gelatinous layer (Panshin and de Zeeuw, 1980). The degree of variation in density is largely dependent on the organization of the cell wall. Woods with thick walled gelatinous fibres can increase density by as much as 5 to 30 percent when compared to normal wood (Panshin and de Zeeuw, 1980; Zobel and van Buijtenen, 1989).

In the past, it was assumed that tension wood was identical to compression wood and could be easily identified through irregularities in growth when viewed in the cross section; however, it has been noted that tension wood often forms with little evidence of unusual growth patterns and thus is difficult to detect (Tsoumis, 1991). It is now assumed that tension wood occurs frequently yet unpredictably throughout the stem (Cutter *et al.,* 2004; Maeglin, 1978; Panshin and de Zeeuw, 1980; Zobel and van Buijtenen, 1989). Maeglin (1978) noted that tension wood may be formed at any time in the life of a tree and is particularly prevalent in young stems.

HEARTWOOD AND SAPWOOD

After initially being formed in the cambium, the most recent growth rings in a tree serve a number of vital roles, including; structural support, conduction of sap and storage of reserve food resources (Jozsa and Middleton, 1994; Keith and Kellogg 1981; Panshin and de Zeeuw, 1980). Although all tracheids are dead in this region, parenchyma cells remain alive as long as they reside in the sapwood zone. Thus, this light coloured growth nearest to the bark is known as sapwood and is thought of as the living component of the wood (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Jane, 1956; Jozsa and Middleton, 1994). The thickness and overall size of this band of sapwood is dependent on the species of tree, its age, and overall rate of growth (Keith and Kellogg 1981; Panshin and de Zeeuw, 1980; Sterrett, 1917; Wilson and White; 1986).

Sapwood thickness can vary considerably within an individual species and is directly related to the dominance of the tree within the stand, site conditions, and available resources (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Jane, 1956; Keith and Kellogg 1981). Within an individual tree, sapwood thicknessis largest in the crown section of the tree and decreases in width toward the base, forming a conical shape within the stem (Keith and Kellogg 1981; Panshin and de Zeeuw, 1980).

After a number of years, the living components of the sapwood begin to die and form wood known as heartwood (Bowyer *et al.,* 2003; Jozsa and Middleton, 1994; Keith and Kellogg 1981; Tsoumis, 1991). The transition from sapwood to heartwood is accompanied by the production of new compounds known as extractives (Desch and Dinwoodie, 1981). The accumulation of extractives gives heartwood its distinguishable yellow, red or brown shades in comparison to the outer sapwood (Jozsa and Middleton, 1994; Keith and Kellogg 1981; Panshin and de Zeeuw, 1980; Schumann, 1973; Tsoumis, 1991).

It is thought that the process of heartwood transition is initiated, first, through decreased moisture content in the inner part of the tree and secondly, through the transport of excess quantities of food resources unnecessary for the photosynthetic activities of the tree (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980). These sugar rich reserve materials are eventually transformed into extractives, including; tannins, gums, waxes, acids and volatile oils (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980).

The accumulation of extractives and other materials within the heartwood encrusts the vessels and plugs the pits of cells, severely reducing water flow and permeability within the heartwood (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980). This loss of permeability makes heartwood more durable than sapwood and increases resistance to fungal decay (Keith and Kellogg 1981). However, this reduced permeability causes difficulty in many manufacturing processes including wood impregnation techniques, pulping and drying (Keith and Kellogg 1981; Panshin and de Zeeuw, 1980).

Extractives can be present in high enough quantities to increase hardness and compressive strength values, although this affect is thought to be minor (Keith and Kellogg 1981). Extractives are thought to significantly increase the weight and density of heartwood in comparison to sapwood at the same moisture content (Bowyer *et al.,* 2003). However, in freshly felled trees, the moisture content of the sapwood varies considerably with species, season and environmental conditions (Keith and Kellogg 1981). In softwoods, the sapwood can have significantly more moisture and weight then the heartwood. In many ring porous hardwoods, the heartwood contains a higher moisture content than the sapwood. In these species, the moisture content rises rapidly from the inner sapwood to the boundary of the heartwood. As there is no movement of water in the heartwood, the moisture content does not fluctuate (Keith and Kellogg 1981; Panshin and de Zeeuw, 1980)..

It is impossible to determine the age when heartwood production begins and at what rate sapwood will be converted (Bowyer *et al.,* 2003; Panshin and de Zeeuw, 1980). Species that are inefficient in resource utilization will begin the formation of heartwood at a young age and will contain a narrow sapwood band and wide heartwood band (Keith and Kellogg 1981). A more efficient species will contain wider sapwood and less heartwood. However, the transition seems to be regulated in part by the age since the wood was originally formed and the distance it sits from the active cambium. Thus, trees with wide annual rings transition more quickly to heartwood but also have wider areas of sapwood. Slower growing trees have narrow bands of sapwood containing numerous growth rings (Bowyer *et al.,* 2003; Keith and Kellogg 1981; Panshin and de Zeeuw, 1980).

WOOD QUALITY AND MECHANICAL PROPERTIES

An understanding of a materials properties, characteristics and qualities is vital to its utilization (Jozsa and Middleton, 1994; Maeglin, 1976; Markwardt and Wilson, 1935; Tsoumis, 1991; Zhang, 2003). This is particularly true of wood given its complex nature and high variability (Jozsa and Middleton, 1994). However, wood quality is difficult to define, as it is largely dependent on the attributes desired for a particular end product or consumer (Cutter *et al.,* 2004; Jozsa and Middleton, 1994; Kellogg, 1982, Larson, 1969). Qualities desired for one product may be largely inferior or unusable for another (Jozsa and Middleton, 1994; Kellogg, 1982). For example, the wood quality attributes most valuable in the pulp and paper industry include fibre length and chemical composition while the attributes desired for lumber in home construction include high density, small knots and straight grain (Jozsa and Middleton, 1994; Zhang, 2003). Other users may desire wood of high aesthetic quality for furniture and novelty items, while wood with high thermal value has become increasingly important in an era of high heating and energy production costs (Zhang, 2003).

In recent years the definition of wood quality has been broadly expanded to provide a more comprehensive view of wood quality and end use attributes; moving from a simple relation of wood properties and particular end uses to a holistic view of the entire value recovery chain (Zhang, 2003). This includes all aspects of harvesting, manufacturing, serviceability and end utilization (Zhang, 2003).

In the context of this study, selected mechanical properties were examined to provide a more complete understanding of the potential utilization of black ash with a focus on solid wood products.

Mechanical Properties

Mechanical properties are a measure of a material's strength and resistance to deformation (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Garrat, 1931; Hoadley, 2000; Tsoumis, 1991). Strength is defined as the ability of the material to bear load without becoming deformed or distorted (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996), whereas resistance to deformation is a measure of how a material is altered in response to load (Bowyer *et al.,* 2003; Tsoumis, 1991). These properties are measured utilizing a variety of methods and largely determine the end utilization and application of wood products (Garrat, 1931, Markwardt and Wilson, 1935).

Two concepts are essential to the understanding of mechanical properties; stress and strain (Garrat, 1931; Hoadley, 2000). Stress is a measure of force per unit area (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Hoadley, 2000; Tsoumis, 1991). There are three primary forces of stress: tensile, compression and shear (Figure 8) (Garrat, 1931, Hoadley, 2000; Tsoumis, 1991;). Under the forces of these stresses, wood tends to distort and deform in its shape and size. The measurement of these changes is known as strain and is defined as the amount of deformation in the wood due to stress (Desch and Dinwoodie, 1996; Garrat, 1931; Hoadley, 2000).

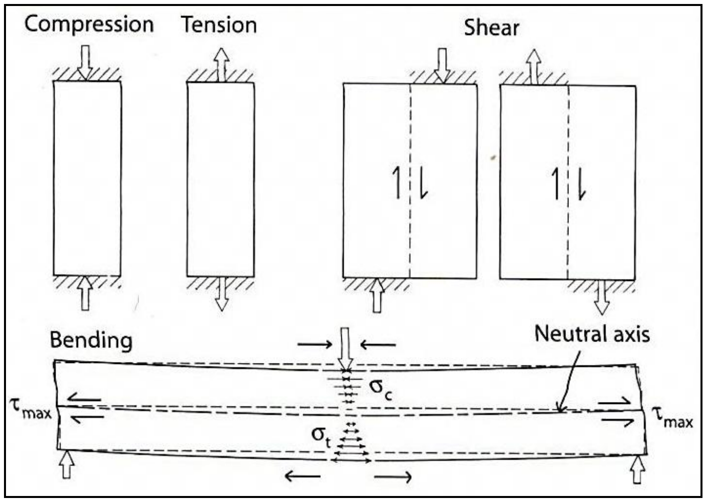

Figure 8. The three primary forms of stress and their combined affect in bending (Hoadley, 2000).

The relationship between stress and strain is linear, in that each increment of stress creates a comparative level of strain (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Garrat, 1931; Hoadley, 2000; Tsoumis, 1991). This relationship continues below the proportional limit, where wood is elastic in nature and is able to recover from applied stresses (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Garrat, 1931; Hoadley, 2000; Tsoumis, 1991). Beyond this limit, each additional increment of stress causes larger increments of strain and permanent deformation; to the point of ultimate failure (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Garrat, 1931; Hoadley, 2000; Tsoumis, 1991). The slope of the linear relationship between stress and strain is known as the modulus of elasticity or young's modulus (Bowyer *et al.,* 2003; Hoadley, 2000; Tsoumis, 1991). Figure 9 depicts the relationship between stress and strain.

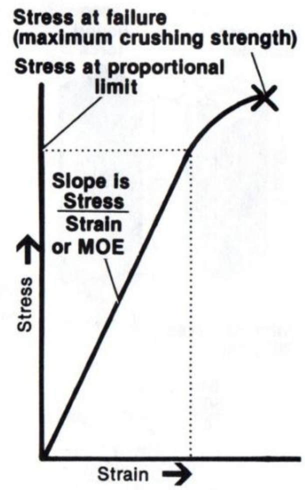

Figure 9. Relationship between stress and strain as shown in a compression parallel to grain test (Bowyer *et al.,* 2003).

Strength, as defined above, is often used as a general term in reference to all mechanical properties (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Garrat, 1931). However, more precisely, strength is a resistance to stress of a single kind (Garrat, 1931; Markwardt and Wilson, 1935). It is important to be clear in regards to the type of mechanical property being discussed (Bowyer *et al.,* 2003). Species that rank highly in one property may rank poorly in another (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Garrat, 1931; Markwardt and Wilson, 1935). Relevant mechanical properties, their usage, and importance are listed in Table 2.

Table 2. Relevant mechanical properties, their usage, and importance.

Mechanical Property	Value of Test
Strength Properties	
Modulus of Rupture	Determines the load a beam can carry; a measure of stress in bending at failure
Compression parallel to grain	Determines the load a column will carry; shortening of fibres lengthwise
Compression perpendicular to grain	Connections between wood members; compaction beyond the proportional limit
Shear parallel to grain	Determines load carrying capacity of short beams; resistance of internal slipping along the grain
Side Hardness	Resistance to wear and denting of foreign objects;
Elastic Properties	
Modulus of Elasticity	Determines the stiffness or rigidity of a beam; resistance to bending
Young's Modulus	Resistance to elongation or shortening under uniform tension or compression

Source: (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Hoadley, 2000; Kretschmann, 2010; Markwardt and Wilson, 1935; Tsoumis, 1991)

The difficulty in measuring mechanical properties stems from the inherent qualities of wood. Wood is heterogeneous, meaning it is subject to differences between species, environmental variability and a wide variety of irregularities and defects (Garrat, 1931; Hoadley, 2000; Kretschmann, 2010; Tsoumis, 1991). It also is anisotropic, which means properties vary with the direction of measurement; radially, longitudinally, and tangentially (Figure 10) (Bowyer *et al.,* 2003; Hoadley, 2000; Kretschmann, 2010; Tsoumis, 1991).

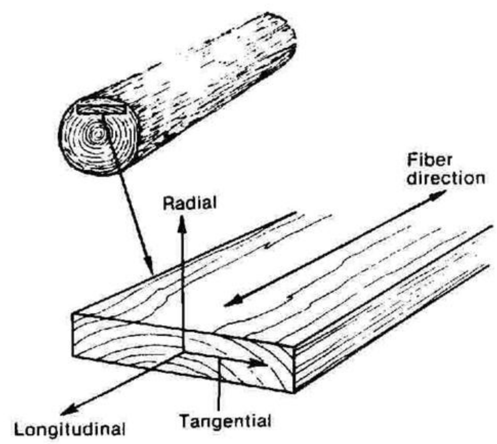

Figure 10. Directions of measurement in wood properties (Bowyer *et al.,* 2003).

Mechanical properties of wood are determined from small, clear and defect-free specimens of wood that are maintained at a set moisture content and temperature (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Hoadley, 2000; Tsoumis, 1991). Tests of larger specimens, structural lumber and beams are also performed (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Garrat, 1931; Markwardt and Wilson, 1935; Tsoumis, 1991). However, small, clear samples allow for the possibility of increased sampling intensity and the ability to more accurately study the effects of various external factors (Desch and Dinwoodie, 1996; Garrat, 1931; Hoadley, 2000).

In North America, published values of mechanical properties are aggregated into averages for individual species in an attempt to cover the range in variation of each species (Table 3) (Garrat, 1931; Jessome, 1977; Markwardt and Wilson, 1935). Jessome (1977) compiled research on mechanical properties in Canada dating back 50 years and summarized these values on a national basis. Alemdag (1984) and Singh (1986) evaluated density of species across Canada. Markwardt and Wilson (1935) investigated mechanical properties of species across the United States. However, little attention has been paid to underutilized species and significant gaps remain in the location of sample sites across the growth range of many species (Singh, 1986).

The values in Table 3 support evidence that mechanical properties are influenced by a number of factors, namely: temperature, moisture content, density, and internal characteristics and defects (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Garratt, 1931; Hoadley, 2000; Tsoumis, 1991).

Temperature

The mechanical properties of wood respond to changes in temperature (Figure 11) (Desch and Dinwoodie, 1996; Garrat, 1931; Hoadley, 2000). In general, strength in all properties is reduced with increasing temperature (Bowyer *et al.,* 2003; Koehler, 1933; Tsoumis, 1991). Hoadley (2000) notes that for every 12°C increase in temperature there is a corresponding two to five percent drop in strength properties. Desch and Dinwoodie (1996) suggest a 1°C increase in temperature results in a one percent reduction in strength. However, the effect of temperature is reversible and is closely tied to the moisture content of the wood (Desch and Dinwoodie, 1996).

Table 3. Values of mechanical properties in black ash and similar species across North America.

Species	Source	Locations	Number of Sample Trees (Locations)	Mositure Content	Density (kg/m3)	Shrinkage: Radial (%)	Shrinkage: Tangential (%)	Shrinkage: Volumetric (%)	Static Bending: MOR (MPa)	Static Bending: MOE (Mpa)	Impact Bending: MOE (Mpa)	Impact Bending: Hammer Drop (mm)	Compression Parallel: MOE (Mpa)	Compression Parallel: Max. Crushing Stress (Mpa)	Comp. Perpend.: Stress at Prop. Limit (Mpa)	Hardness: Side (N)	Hardness: End (N)	Shear Parallel: Max. Shear Stress (Mpa)	Cleavage: Splitting Strength (N/mm Width)	Tension Perpend.: Max. Stress (MPa)
Black Ash	Jessome (1977)	ON	6 (1)	Green	468	4.3	8.2	13.8	43.9	8550	8140	1520	9930	16.7	2.61	3270	3380	5.76	60.9	4.47
				12%	494	-	-	7.9	84.0	13500	12700	1420	13900	40.8	5.84	4220	4900	12.12	75.7	4.92
	Markwardt & Wilson (1935)	MI, WI	5 (2)	Green	450	15.2	5.0	7.8	41.4	7171	-	838	-	15.9	2.96	2313	2624	6.00	31.6	3.38
				12%	490	-	-	-	86.9	11032	-	889	-	41.2	6.48	3781	5115	10.76	42.9	4.83
	Almedag (1984)	ON	18	Green	545	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
White Ash	Jessome (1977)	ON,NB	13(2)	Green	570	4.2	7	13.1	57.4	9930	12200	1930	11000	25.4	5.35	4660	4820	9.49	83.5	6.54
				12%	613	-	-	7.2	108.0	12800	16300	1420	13500	49.8	10.00	7050	8570	14.80	87.4	7.42
	Markwardt & Wilson (1935)	AK, NY, WV, VT, MA	23(5)	Green	550	13.3	4.9	7.9	66.2	10066	-	1092	-	22.0	5.58	4270	4493	9.51	37.3	4.07
				12%	600	-	-	-	106.2	12204	-	965	-	39.9	9.72	5872	7651	13.44	54.2	6.48
	Kraemer (1956)	IL, IND, KT, MI, NY, MO	40(8)	Green	650	-	-	-	59.7	8887	-	-	-	21.3	5.84	4844	4920	8.30	-	-
				12%	677	-	-	-	101.9	11928	-	-	-	46.4	11.91	7184	-	13.29	-	-
	Almedag (1984)	ON	64	Green	594	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Green Ash	Jessome (1977)	MB	2(1)	Green	486	3.8	5.4	11.4	34.7	5720	8200	1070	6830	14.8	3.57			6.81	56.4	4.76
				12%	506	-	-	8.3	55.6	6960	-	-	11700	32.5	7.31			9.72	70.2	6.43
	Markwardt & Wilson (1935)	LA, MO	10(2)	Green	530	12.5	4.6	7.1	65.5	9653	-	889	-	29.0	6.27	4270	4270	8.69	39.5	4.07
				12%	560	-	-	-	97.2	11445	-	813	-	48.8	11.17	7251	7251	13.17	49.7	4.83
	Singh (1986)	AB, SK, MB	20	Green	590	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Red Oak	Jessome (1977)	QC, ON	11(2)	Green	581	3.6	6.7	12	64.5	10800	15000	1600	10800	27.2	5.44	4590	5530	9.38	85.1	6.54
				12%	612	-	-	6.9	98.7	11900	17100	1450	13700	49.8	8.89	6170	7340	14.38	85.5	6.52
	Markwardt & Wilson (1935)	LA	4(1)	Green	520	16.3	4.5	8.7	47.6	7860	-	737	-	20.9	4.69	4048	3025	6.41	31.6	3.31
				12%	590	-	-	-	75.2	10273	-	660	-	42.0	7.45	4537	4537	9.58	39.5	3.52
	Almedag (1984)	ON	100	Green	590	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sugar Maple	Jessome (1977)	QC, ON, NB	19(4)	Green	597	4.6	8.8	15.7	70.5	11700	17700	1370	13000	31.4	5.89	5230	5920	11.14	93.2	7.18
				12%	659	-	-	9.3	115.0	14100	24000	1450	15400	56.4	9.72	7290	8780	16.71	110.0	9.21
	Markwardt & Wilson (1935)	IN, PA, VT, WI	17(4)	Green	560	14.9	4.9	9.5	64.8	10687	-	1016	-	27.7	5.52	4315	4760	10.07	-	-
				12%	630	-	-	-	108.9	12617	-	991	-	54.0	12.48	6450	8185	16.06	-	-
	Almedag (1984)	ON	86	Green	616	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
White Birch	Jessome (1977)	NB, MB, SK	16(3)	Green	506	5.2	7.2	13.8	47.2	10000	12200	1930	11000	25.4	5.35	4660	4820	9.49	83.5	6.54
				12%	571	4.4	6.6	10.5	94.8	12900	16300	1420	13500	49.8	10.00	7050	8570	14.80	87.4	7.42
	Markwardt & Wilson (1935)	WI, NH	10(2)	Green	480	16.2	6.3	8.6	44.1	8067	-	1245	-	16.3	2.34	2491	2091	5.79	23.7	2.62
				12%	550	-	-	-	84.8	10963	-	864	-	39.2	5.10	4048	3959	8.34	61.0	-
	Almedag (1984)	ON	44	Green	539	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Source: (Almedag, 1984; Jessome, 1977; Kraemer, 1956; Markwardt and Wilson, 1935; Singh, 1986)

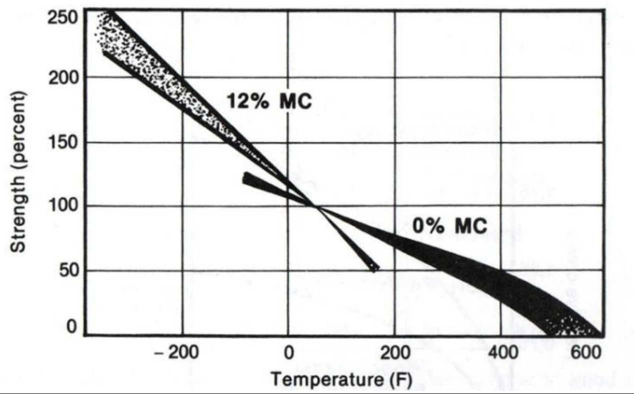

Figure 11. Effect of temperature on wood properties (Bowyer *et al.,* 2003).

Moisture Content

Moisture content (MC) is a measure of the weight of water contained in wood and is expressed as a percentage of the wood's oven dry weight. MC is expressed in one of three ways; oven- dry condition, nominal condition (12 percent MC), and green condition (basic specific gravity), which is at or above the fibre saturation point (Bowyer *et al.,* 2003; Eckelman, 1997; Porter, 1981; Tsoumis, 1991).

MC affects the mechanical properties of wood as it drops below the fibre saturation point (Figure 12) (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Tsoumis, 1991). In general, as MC decreases, strength and elastic property values increase (Bowyer *et al.,* 2003; Hoadley, 2000; Tsoumis, 1991). This increase is a direct result of moisture loss in the cell wall. As water is removed, the cells walls become more compact with a greater volume of wood substance in a given area (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Jozsa and Middleton, 1994; Tsoumis, 1991).

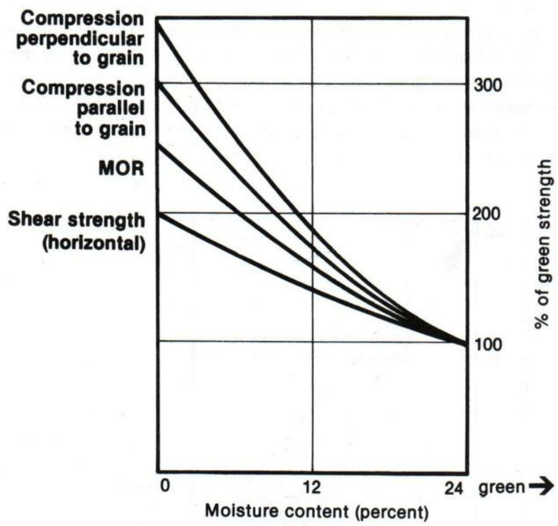

Figure 12. Affect of moisture content on selected wood properties (Bowyer *et al.,* 2003).

<u>Density</u>

Given the porous, cellular makeup of wood; the amount of solid wood substance present in a given volume of wood is a good indication of its overall strength (Bowyer *et al.,* 2003; Eckelman, 1997; Hoadley, 2000; Jozsa and Middleton, 1994; Koehler, 1933; Kraemer, 1956; Porter, 1981; Tsoumis, 1991). Two measurements are commonly used to quantify the porosity of wood, density and specific gravity (Porter, 1981). The calculated values of both density and specific gravity are directly related to the MC of the wood. Thus, it is critical to state the MC at which the density or specific gravity values were obtained (Eckelman, 1997; Jozsa and Middleton, 1994; Panshin and de Zeeuw, 1980).

Density is a measure of mass per unit volume and is typically reported as kilograms per metre cubed (kg/m^3) (Desch and Dinwoodie, 1996; Panshin and de Zeeuw, 1980). Density is calculated using the weight and moisture content of wood at the time of measurement, using Equation 2.

$$D_{M.C.} = \frac{W_{M.C.}}{V_{M.C.}}$$

Where; (Equation 2)

$D_{M.C.}$ = density at specific moisture content
$W_{M.C.}$ = weight of wood with specific moisture content
$V_{M.C.}$ = volume of wood with specific moisture content
(Panshin and de Zeeuw, 1980)

It is accepted that the density of solid cell wall material within any tree species is approximately 1500 kg/m^3, with the density of the actual cell wall material constituting nearly the same density when in the oven dry state (Desch and Dinwoodie, 1996; Garrat, 1931; Jozsa and Middleton, 1994; Panshin and de Zeeuw, 1980). As MC increases within the wood, the micro-cavities expand and reduce the density of the cell wall below that of solid wood substance (Panshin and de Zeeuw, 1980).

As MC decreases within the wood so do the corresponding density values. The minimum values for density occur in the oven dry state and are highest when in the green condition. This holds true as both the weight of the sample and the volume decrease in relation to decreased moisture content (Eckelman, 1997; Panshin and de Zeeuw, 1980).

Relative density (RD), also referred to as specific gravity, is a ratio of the mass of a substance to an equal volume of water at a known temperature, typically four degrees Celsius.

RD is used to standardize comparison of density values between species and thus has no specified unit (Desch and Dinwoodie, 1996; Panshin and de Zeeuw, 1980; Simpson and TenWolde, 1999). RD is always calculated with oven dry mass as the numerator (Equation 3). However, the displaced volume of water is dependent on the volume of the sample and is thus dependent on shrinkage caused by the MC within the wood. RD must always be reported with the moisture content of the wood with which the volume was determined as seen in Equation 4 (Eckelman, 1997; Panshin and de Zeeuw, 1980).

$$SG = \frac{W_{o.d.}}{W_{d.w.}}$$

Where; (Equation 3)

SG = specific gravity
$W_{o.d}$ = weight of wood at oven dry
$W_{d.w.}$ = weight of displaced volume of water
(Panshin and de Zeeuw, 1980)

$$SG_{MC} = (W_{od}/V_{od})/P_w$$

Where; (Equation 4)

W_{od} = oven dry weight,
V_{od} = oven dry volume and;
P_w = density of water
(Simpson 1993; Panshin and de Zeeuw, 1980)

As MC decreases, the volume of the wood becomes smaller and the RD value increases. The minimum values for RD are obtained in the green condition and the highest values obtained in the oven dry condition. Similar to density, this holds true as the measured oven dry weight remains constant but the volume decreases in relation to decreased MC (Eckelman, 1997; Panshin and de Zeeuw, 1980).

Internal Defects

The structure of wood can have a significant effect on properties (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Garratt, 1931; Tsoumis, 1991). Factors previously discussed including, earlywood and latewood, growth rate, tension wood, and extractives are all capable of altering the internal structure and resulting density and mechanical properties of wood (Bowyer *et al.,* 2003; Garrat, 1931). Internal defects, including, knots, decay and grain deviation will reduce the strength of wood significantly and are generally avoided in mechanical testing (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996; Garrat, 1931; Hoadley, 2000; Markwardt and Wilson, 1935; Tsoumis, 1991).

VARIATION WITHIN TREES

It has been widely documented within the literature that properties vary within a tree in three distinct ways (Koga and Zhang, 2004; Panshin and deZeeuw, 1980; Zobel and van Buijtenen, 1989). The most studied and well-known form of variation within trees is radially; from pith to bark (Abdel-Gadir and Krahmer, 1993; Park *et al.,* 2009; Phelps and Workman, 1994). All trees also have properties that vary longitudinally, from stump to crown (Hildebrandt, 1960; Park *et al.,* 2009; Zhang *et al.,* 2004; Zobel and van Buijtenen, 1989). However, the greatest variation occurs among the cells that make up each individual growth ring (Jozsa and Middleton, 1994; Keith and Kellogg, 1981; Megraw, 1985; Pliura *et al.,* 2006; Zobel and van Buijtenen, 1989).

Within A Growth Ring

The within ring patterns of variation are complex and can be attributed to the differing characteristics of earlywood and latewood within the ring (Koubaa *et al.,* 2002; Panshin and de Zeeuw, 1980; Pliura *et al.,* 2006; Tsoumis, 1991). As Zobel and van Buijtenen (1989) noted, the distribution and characteristics of cells within the earlywood and latewood has the greatest effect on the variation in properties (Keith and Kellogg, 1981; Koubaa *et al.,* 2002; Pliura *et al.,* 2006; Zobel and van Buijtenen, 1989).

As discussed previously, cells found in the earlywood portion of the ring display thin walls and large lumen spaces (Fries and Ericsson 2008; Keith and Kellogg 1981; Panshin and de Zeeuw, 1980). Ring porous hardwoods also contain a large proportion of vessels within the earlywood (Hoadley, 1990). The volume and diameter of vessels decreases into the latewood, which is composed almost entirely of smaller fibres, characterized by thicker walls and smaller lumen spaces (Keith and Kellogg, 1981; Panshin and deZeeuw, 1980; Zobel and van Buijtenen, 1989). The thicker cell walls, smaller lumen spaces and fewer vessels within the latewood result in an increased density (Woodcock and Shier, 2002).

Zobel and Talbert (1984) describe the relationship of cell wall thickness and cell size to density in Figure 13. Given two cells of the same type, each with identical cell wall thicknesses, though one cell is larger, the larger cell will have a lower density. Likewise, given two cells that have similar sizes but varying cell wall thicknesses, the cell composed of the thicker cell wall will have a higher density.

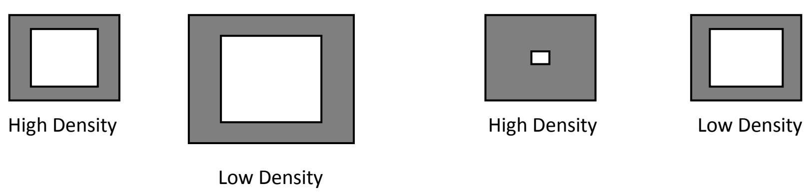

Figure 13. Effects of cell size and wall thickness on density (Zobel and Talbert 1984).

The pattern of density change in hardwoods is highest in the latewood and lowest in the earlywood (Panshin and deZeeuw, 1980; Pliura *et al.,* 2006; Zhang *et al.,* 1994; Zobel and van Buijtenen, 1989). Thus in ring porous hardwoods, the variation in density within an individual growth ring is influenced largely by the proportion of latewood within that ring (Hamilton, 1961; Zhang, 1995; Zhang *et al.,* 2004; Zobel and van Buijtenen, 1989).

From year to year, the width of the earlywood remains fairly consistent in ring porous species regardless of growth rate (Phelps and Workman, 1994; Zhang, 1995). The percentage of latewood is affected most readily by variations in growth rate (Fukazawa, 1984; Phelps and Workman, 1994; Sterrett, 1917; Zhang, 1995). Thus, favourable conditions will result in increased ring width and larger amounts of latewood while unfavourable conditions result in decreased amounts of latewood and smaller ring widths (Fukazawa, 1984; Zobel and van Buijtenen, 1989).

Ring width is directly related to the density within a tree (Zhang, 1995). In ring porous species, slower growth produces less dense wood, while faster growth results in more dense wood (Fukazawa, 1984; Guiher, 1965; Phelps and Workman, 1994; Zhang, 1995; Zobel and van Buijtenen, 1989).

Little is understood in regards to the effect of ring width on mechanical properties in most hardwoods (Zhang, 1995). Zobel and van Buijtenen (1989) note that literature is available to support any pattern. However, Zhang (1995) states that the relationship in ring porous woods is direct and consistent. Increased density resulting from larger ring widths produces improved mechanical properties given the positive influence of density on mechanical properties.

Fibre and vessel element length can vary considerably within individual growth rings (Keith and Kellogg, 1981; Panshin and de Zeeuw, 1980; Taylor, 1979). Variation can be as large as 80 percent in short fibered species and 15 percent in long fibered species (Keith and Kellogg, 1981). The pattern of variation is closely related to the degree of contrast between the earlywood and latewood, as latewood fibers are longer then earlywood fibers (Chalk, 1970; Denne and Whitbread, 1978; Keith and Kellogg, 1981; Saucier and Hamilton, 1967). Thus, ring porous species with highly contrasting earylwood and latewood display more distinct variation in fibre length when compared to diffuse porous species (Keith and Kellogg, 1981; Taylor, 1975). As noted by Taylor (1975), ring porous woods display a definite increase in fibre length from earlywood to latewood.

As stated, density is closely correlated with mechanical properties and thus the effect of differing density between earlywood and latewood on finishing and product quality can be significant (Herajarvi, 2001; Phelps and Workman, 1994; Zobel and van Buijtenen, 1989). Biblis (1969) found that latewood had greater than 50 percent higher specific stress and stiffness values then that of earlywood. The contrast between the softer earlywood and harder latewood, known as uniformity or texture, can result in a coarse surface when finishing and can lead to splitting, machining difficulty and severe drying distortions (Herajarvi, 2001; Phelps and Workman, 1994; Zobel and van Buijtenen, 1989).

Lack of uniformity in ring porous species limits its potential for manufactured panels and particle boards but increases its potential for appearance products (Herajarvi, 2001; Phelps and Workman, 1994). As Phelps and Workman (1994) note, texture is an important feature for woods utilized in veneers. However, as discussed, increased proportions of latewood in ring porous species is desirable, given the increase in mechanical properties. Phelps and Workman (1994) noted that this wood is harder, denser, and stronger and has a greater durability.

Radial Variation

Radial variation trends exist for all hardwood species and vary greatly in magnitude and pattern (Jozsa and Middleton, 1994; Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998). Some trends are of key importance to wood properties, while others have little effect (Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998). Density is the single most important property evaluated and thus contains the largest amount of available literature (Evans *et al.,* 2000; Zobel and van Buijtenen, 1989).

Panshin and de Zeeuw (1980) noted that over half of the hardwoods that have been examined for radial patterns of density variation exhibit a trend of increasing density from pith to bark. Woodcock and Shier (2002) found increases in three diffuse porous northern hardwoods. However, Parker *et al.,* (1978) and Harrington and DeBell (1980) noted little significant variation in diffuse porous species including *Alnus rubra* Bong. Zobel and Sprague (1998) attribute this trend to the lack of significant difference between juvenile and mature wood in some species.

A number of studies have stressed that density of ring porous hardwoods is highest near the pith and decreases towards the bark (Burdon *et al.,* 2004; Fukazawa, 1984; Hamilton, 1961; Paul, 1930; Paul, 1960; Phelps and Chen, 1989; Springer and Olsen, 1987; Wheeler, 1987; Woodcock and Shier, 2002; Zhang *et al.,* 2004; Zobel and Sprague, 1998). Other studies have noted this trend and suggested that a slight increase in density may occur towards the bark in more mature trees (Panshin and de Zeeuw, 1980; Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998).

Consistent with this trend, Rink and McBride (1993) found that the heartwood of *Quercus sp*. had a specific gravity of 0.55 to 0.57 while the sapwood had a specific gravity of 0.51 to 0.54. Paul (1963) reported that sapwood in *Juglans nigra* L. had a lower specific gravity then heartwood.

The trends in density variation found in ring porous woods can be attributed to the decreasing amounts of latewood within the growth ring as the distance from the pith increases (Fukazawa, 1984; Wheeler, 1987; Woodcock and Shier, 2002). Zobel and Sprague (1998) and Fukazawa (1984) noted that juvenile wood in ring porous woods is thought to have a higher density then that of mature wood. Clarke (1930) and Keith and Kellogg (1981) identified that the growth rings nearest the pith often lack the distinct earlywood vessels and characteristic ring porous structure found in later rings and thus have a higher density.

Montes *et al.,* (2007) noted that radial density variation is less for denser hardwoods than for less dense species. Woodcock and Shier (2002) state that lighter woods display increases in density while denser woods display decreases from pith to bark. They further suggest that species with radial increases in density have lower initial density values then those species showing radial decreases.

Several studies have noted that radial increases in density, in combination with low density, are a trait of early successional species; while radial decreases, associated with high density, are a trait of late successional species (Montes *et al.,* 2007; Woodcock and Shier, 2002).

The trend of radial increases and early successional species has been well documented in tropical species (Wiemann and Williamson, 1988; Woodcock and Shier, 2002).

Woodcock and Shier (2002) and Pliura *et al.,* (2006) further note that the theory of a general pattern of radial variation often disguises the fact that many patterns of radial variation exist within trees and are a result of the microclimates these trees are located in. They further suggest that young trees produce low or high-density wood, dependent on these microclimates, whereas older trees tend to converge upon a sort of optimal density. Thus, the range in density variation should be largest near the pith (Stringer and Olsen, 1979; Woodcock and Shier, 2002).

Research into radial variation in other mechanical properties is somewhat limited and quite contradictory (Hamilton, 1961; Zobel and Sprague, 1998). Every possible pattern of variation exists based on the species and measured property (Zobel and van Buijtenen, 1989). For example, Herajarvi (2004) found that both modulus of elasticity and modulus of rupture increased steadily from pith to bark in mature *Betula spp*. Hamilton (1961) found that hardness and toughness values were greatest at the pith and decreased towards the bark in *Quercus spp*. Clarke (1935) and Sterrett (1917) stated the best quality wood was located three to seven inches from the centre of the pith and decreased rapidly towards the bark. These results were in contrast to Koehler (1933) who found no relationship between toughness and radial distance in *Fraxinus spp*.

Radial variations in cell structure and fibre length have been studied extensively for many years by the pulp and paper industry (Keith and Kellogg, 1981; Zobel and van Buijtenen, 1989). However, most research has focused on softwood species, which demonstrate an increase in tracheid length from pith to bark (Myer, 1930; Saucier and Hamilton, 1967; Zobel and Sprague, 1998). It is widely assumed a similar pattern exists in hardwoods (Hamilton, 1961; Myer, 1930; Stringer and Olsen, 1979; Taylor and Wooten, 1973). Denne and Whitbread (1978) and Saucier and Hamilton (1967) demonstrated a rapid increase in fibre length in *Fraxinus spp.* for the first decade followed by a more gradual increase. Other authors suggest a rapid increase in cell length in newly formed wood that can continue from 40 to 100 years (Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998). Further evidence suggests that the shorter lived the species, the more quickly mature cell dimensions are reached (Zobel and van Buijtenen, 1989).

As discussed earlier, juvenile wood in hardwoods produces wood with distinct differences in cell distribution from that of mature wood. Vessels in juvenile wood are capable of producing different shapes or structures than that of mature wood (Keith and Kellogg, 1981; Zobel and van Buijtenen, 1989). Most importantly, the typical ring porous structure of some hardwoods can be incomplete or lacking within the juvenile wood (Clarke, 1930, Keith and Kellogg, 1981; Zobel and van Buijtenen, 1989).

The chemical composition of wood appears to display patterns of radial variation (Keith and Kellogg, 1981). Cellulose content is higher in the juvenile portion of the tree while lignin content gradually decreases from pith to bark (Keith and Kellogg, 1981; Zobel and van Buijtenen, 1989). The quantity of extractives generally increases towards the pith with increased proportions of decay resistant extractives within the heartwood (Keith and Kellogg, 1981; Stringer and Olsen, 1979).

Longitudinal Variation

Longitudinal variation in wood properties occurs within trees due to changes in characteristics and relative percentages of juvenile and mature wood throughout the length of the main stem (Hamilton, 1961; Park *et al.,* 2009; Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998). However, in most cases, longitudinal variation seems to be less prominent when compared to radial variation (Keith and Kellogg, 1981; Zobel and van Buijtenen, 1989).

Patterns of longitudinal variation in hardwoods demonstrate very little consistency and no dominant pattern (Alemdag, 1984; Panshin and deZeeuw, 1980; Park *et al.,* 2009; Zobel and van Buijtenen, 1989). Density, one of the most studied properties, demonstrates this reality. In a major study of 28 species, Okkonen *et al.,* (1972) found that 17 species had decreasing density towards the crown, five had increasing density, three had slight decreases before increasing towards the crown, and three demonstrated no change from stump to crown.

However, it is safe to assume that differing densities occur within varying heights in the tree (Alemdag, 1984; Fukazawa, 1984; Hildebrandt, 1960; Jane, 1956). As Van Buijtenen (1969) noted, the difference between the butt and top log of most trees is significantly greater than the butt logs of separate trees. Both Jane (1956) and Markwardt and Wilson (1935) state that butt logs are often more dense than those obtained higher in the stem (Myer, 1930; Stringer and Olsen, 1979; Taylor, 1979). Fukazawa (1984) theorized that excessive root swelling could affect the composition of juvenile wood and growth stresses in the lower bole. This theory did not apply in the unique case of swollen butts found on extremely wet sites, which demonstrate an opposite trend (Jane, 1956; Koehler, 1933; Kraemer, 1956; Markwardt and Wilson, 1935; Paul, 1963). In contrast, Zobel and Sprague (1998) as well as Fukazawa (1984) and Taylor (1979), state that the top wood in ring porous species is often more dense then the butt as the high percentage of juvenile wood increases the overall density. However, Hamilton (1961) noted that the highest density in *Quercus falcate* Michx. was found in the middle log of the tree.

The literature indicates that the most common trend in longitudinal density variation is to display little change (Manwiller, 1979; Stringer and Olsen, 1987; Taylor 1979; Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989). This trend is often observed when little change exists between juvenile and mature wood (Zobel and Sprague, 1998). Other authors have noted that some species demonstrate high density at the base, a moderate decrease up the stem, followed by an increase towards the top (Panshin and deZeeuw, 1980; Yanchuk *et al.,* 1983; Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989). Some hardwood species have shown a straight increase in density from the base to the crown (Keith and Kellogg, 1981; Manwiller, 1979; Panshin and deZeeuw, 1980; Zobel and Sprague, 1998).

Research into longitudinal trends in other mechanical properties is more limited and indicates little consistency. However, as early as 1930, Myer (1930) observed a position effect in the mechanical properties of *Quercus alba* L. Markwardt and Wilson (1935), Clarke (1938) and Kraemer (1956) noted that the butt logs of ash are often superior in toughness and shock resistance. This was further confirmed by Clarke (1935) in a study on *Fraxinus excelsior L*., Sterrett (1917) on *Fraxinus spp.* and Carmean and Boyce (1974) in a discussion on hardwood log quality. However, as noted, butt logs from extremely wet locations can have lower strength properties (Jane, 1956; Markwardt and Wilson, 1935). The observed change in the butt logs of many trees is distinctive of the general features of wood from the base of the stem. That is, the section of stem with the greatest vertical changes in wood properties as well as rapidly changing properties within the first few metres (Burdon *et al.,* 2004).

In an extensive study of *Quercus falcate* Michx., Hamilton (1961) noted a zone of lower strength through the middle of the stem when measuring hardness and toughness. Consistent with previous research, the highest values were found in the lower section of the stem. However, wood equal in value to that of the base was also observed in the top sections of the stem. Sterrett (1917) and Clarke (1935, 1938) indicated that the higher sections of the stem contain the highest values when measuring compression parallel to the grain. Herajarvi (2004) found that both modulus of elasticity and modulus of rupture decreased slightly from stump to crown in mature birch.

As with radial trends, longitudinal trends in fibre length have been examined in detail. The pattern of variation can differ considerably and a number of examples have been identified (Zobel and van Buijtenen, 1989). The most common pattern observed is to display slightly longer fibres at the base of the tree when compared to the top (Stringer and Olsen, 1987; Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989). However, it is also common to observe essentially consistent fibre length throughout the tree (Myer, 1930; Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989). Other species have shown a gradual increase in fibre length to a maximum point, this is followed by a gradual decrease in fibre length to the top of the stem (Saucier and Hamilton, 1967; Stringer and Olsen, 1987; Tsoumi, 1991; Zobel and van Buijtenen, 1989). The height at which the maximum cell length was reached is dependent on a number of factors including species, height, age, and growth rate (Saucier and Hamilton, 1967).

Regardless of the measured property and apparent trend in variation, longitudinal differences can be attributed almost entirely to the proportion of juvenile and mature wood present within varying parts of the tree (Panshin and de Zeeuw, 1980). As discussed earlier, the unique characteristics of juvenile wood are starkly different than those of mature wood.

SIGNIFICANT INFLUENCES ON WOOD PROPERTIES

Variation in wood properties may occur as a result of any factor that changes or influences the growth pattern of a tree (Larson, 1962; Zobel and van Buijtenen, 1989). These variations are described via phenotypes, which refer to any characteristics of a tree that can be measured, classified or observed (Eriksson and Ekberg, 2006; White *et al.,* 2007). Phenotypic characteristics are influenced by a trees genetic potential and the environment in which it grows (Cutter *et al.,* 2004; Eriksson and Ekberg, 2006; Hildebrandt, 1960; Jozsa and Middleton, 1994; Kraemer, 1956; Panshin and deZeeuw, 1980; Pliura *et al.,* 2006; White *et al.,* 2007; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989; Zobel, 1964). Cutter *et al.,* (2004) further suggests that silvicultural activities also constitute a form of environmental influence.

Both environmental and genetic factors are relevant at the same time (Eriksson and Ekberg, 2006; Hildebrandt, 1960; Panshin and deZeeuw, 1980; White *et al.,* 2007; Zobel and Talbert, 1984; Zobel, 1964). Wood properties are under strong environmental control when they are found to vary with a change in environment (Zobel and Talbert, 1984; White *et al.,* 2007). Properties are under strong genetic control when variation occurs regardless of environmental conditions (Zobel and Talbert, 1984; White *et al.,* 2007). Two prominent examples include wood density and growth rate. Wood density has strong genetic control and is influenced less by environmental factors (Zhang, 1995; White *et al.,* 2007). Growth rate has less genetic control and is influenced largely by environmental influences (White *et al.,* 2007).

Several authors note that cambium age is a significant source of variation in wood properties (Cutter *et al.,* 2004; Hildebrandt, 1960; Panshin and deZeeuw, 1980; Phelps and Chen, 1989; Pliura *et al.,* 2006; Zhang *et al.,* 1990). This "age effect" relates to the production of juvenile and mature wood which is controlled by cambial age (Alteyrac *et al.,* 2006; Fukazawa, 1984; Yang *et al.,* 1986; Zobel and Sprague, 1998; Zobel and van Buijtenen, 1989). As discussed, juvenile wood is defined by structural characteristics and physical properties which are wholly different and largely inferior to those of mature wood (Yang *et al.,* 1986; Zobel and van Buijtenen, 1989).

Genetic Sources of Variation

Properties of wood have strong heritability and cause extensive variation (Jozsa and Middleton, 1994; McGraw, 1985; Savill and Kanowski, 1993; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989; Zobel, 1964). Genetics have a strong influence on how a tree responds to its surrounding environment and can alter form, growth rate, wood morphology, and wood chemistry (Eriksson and Ekberg, 2006; Hildebrandt, 1960; Larson, 1962; Pliura *et al.,* 2006; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989). Some genetic variation is known and can be predicted, while other variation is more random and less understood (Zobel and Talbert, 1984).

Variation can be noted at two significant levels; between species and within species (White *et al.,* 1997; Zobel and van Buijtenen, 1989). Between species variation is well understood and clearly evident in all species. Within species variation can be further examined via geographic variation, stand level variation, tree level variation and within tree variation (van Buijtenen, 1969; White *et al.,* 1997; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989; Zobel, 1964).

Geographic variation results from natural selection favouring species that adapt well to the local environmental conditions (Larson, 1962; White *et al.,* 1997; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989). These adaptations have evolved over generations and are a result of diverse growing conditions across the species natural range (Panshin and deZeeuw, 1980; White *et al.,* 1997). Thus, geographic variation has the greatest interaction of genetic potential and environmental conditions (Zobel and van Buijtenen, 1989).

It is difficult to define geographic variations, as the transition from one area to another is large and often not distinct (White *et al.,* 1997; Zobel and Talbert, 1984). Species with wide variations in climate, elevation and soil type display much geographic variation (White *et al.,* 1997; Zobel, 1964). In Ontario, this variation is displayed and utilized in the form of seed zones across the province (Morgenstern, 1996).

Stand level variation is much smaller then geographic variation and often cannot be accounted for by natural selection (White *et al.,* 1997; Zobel and Talbert, 1984). Variation within a similar geographic area is most often associated with differences in site characteristics (White *et al.,* 1997; Zobel, 1964). However, sources of genetic variation can occur over small areas. Zobel and Talbert (1984) note these differences are frequently in the form of growth characteristics and are often negligible.

The most studied from of genetic variation is at the tree level, between individual trees in the same stand (White *et al.,* 1997; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989; Zobel, 1964). No two trees are genetically identical and the variation in characteristics within trees of the same species, grown on the same site, is often quite large (Larson, 1962; Panshin and deZeeuw, 1980; Zobel and Talbert, 1984). However, genetic differences between trees can be significant or largely unimportant and the exact role of genetics in wood characteristic variation can be difficult to determine (White *et al.,* 1997; Zobel and Talbert, 1984). The combined effect of environmental influences and stand characteristics can often mask genetic variation (Hildebrandt, 1960; Larson, 1962; Panshin and deZeeuw, 1980; Zobel and van Buijtenen, 1989; Zobel, 1964).

Within tree genetic variation is closely related to the variation in properties, both radially and longitudinally, discussed previously (Zobel, 1964; Zobel and van Buijtenen, 1989). Genetic variation has the potential to affect and alter the within tree pattern of wood morphology, growth rate and growth patterns (White *et al.,* 1997; Zobel and Talbert, 1984).

There has been extensive study on the genetic heritability of individual wood properties. However, most literature has focused on commercially valuable species (Eriksson and Ekberg, 2006; Savill and Kanowski, 1993). Cutter *et al.,* (2004) and Zobel (1964) note that there has been a noticeable lack of research in genetic improvement of hardwoods, yet, it is generally assumed that all characteristics of trees have strong heritability (Bendtsen, 1978; Savill and Kanowski, 1993; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989).

Density is consistently the most responsive characteristic to genetic control (Zobel and Talbert, 1984; McGraw, 1985; Zobel, 1964; Bendtsen, 1978; Zobel and van Buijtenen, 1989;

White *et al.,* 1997). Nepveu (1984) determined high broad sense heritability in *Quercus rubra* L. while Cech *et al.,* (1960) found similar results in *Populus trichocarpa* Torr. and A. Gray. A similar trend has been noted extensively in studies focusing on *Populus spp.* and *Eucalyptus spp*. (Zobel, 1964; Zobel and van Buijtenen, 1989).

In a study on *Quercus rubra* L., Nepveu (1984) concluded that the width of the earlywood is under strict genetic control, while the percent of vessels is only under moderate control. Kanowski *et al.,* (1991) reported vessel size in the earlywood to be under strong genetic control.

Zobel and van Buijtenen (1989) note that the percentage of latewood is under strong genetic control. This is of particular interest in the ring porous hardwoods, which rely on increased latewood percentages in the growth ring for increased strength. In contrast, Savill and Kanowski (1993) suggest that environmental conditions largely determine the width of the latewood. Further noting that growth rate is under weak genetic control and thus is a response of environmental conditions.

Environmental Sources of Variation

Differing environmental conditions can result in the production of wood with varying properties (Hildebrandt, 1960; Koehler, 1933; Larson, 1962; Paul, 1963; Pliura *et al.,* 2006; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989). Koehler (1939) believed that environmental conditions were the most important factor influencing wood quality. Zobel and

Talbert (1984) stressed that environmental factors have a great effect on growth factors but less on wood properties. However, Eriksson and Ekberg (2006) suggest that environmental conditions have less of an effect on wood characteristics than genetics, but nonetheless affect growth.

Examples of environmental conditions that have the potential to affect wood characteristics and properties include microsite conditions, soil fertility, climate patterns, photoperiod, and moisture regime (Cutter *et al.,* 2004; Hildebrandt, 1960; Koehler, 1933; Larson, 1962; Markwardt and Wilson, 1935; Panshin and deZeeuw, 1980; Zobel and van Buijtenen, 1989; Zobel, 1964).

Zobel and van Buijtenen (1989) and Panshin and de Zeeuw (1980) note that the variation and related interactions of these factors is so great that it makes them poor indicators of wood property variation within trees. There is also considerable disagreement as to the actual affects these factors have on wood properties (Hildebrandt, 1960; Larson, 1962; Myer, 1930). However, the immense differences in growth range and varying site conditions suggest these environmental factors must alter wood properties and characteristics (Armstrong and Funk, 1980; Polge, 1973; Zobel and Talbert, 1984; Zobel, 1964).

Eriksson and Ekberg (2006), Zobel and Talbert (1984) and Zobel (1964) note extensively that geographic location alters growth rate, growth patterns and tree quality. Significant research undertaken by Alemdag (1984) and Singh (1986) demonstrate extensive variation of density in various Canadian species with geographic location. This variation can largely be attributed to climactic differences between locations (Alemdag, 1984; Hildebrandt, 1960; Myer, 1930; Polge, 1973; Singh, 1986; Wiemann and Williamson, 2002; Zobel and Talbert, 1984).

Zobel and van Buijtenen (1989) noted that many studies indicate stand characteristics have no effect on wood properties, while other studies demonstrated improved wood properties (Carmean and Boyce, 1973; Hamilton and Knauss, 1986; Hildebrandt, 1960; Jayne, 1958; Myer, 1930; Paul, 1963; Polge, 1973; Schumann, 1973). It is evident that research is contradictory and one could find any possible link between stand characteristics and wood properties within the literature (Zobel and van Buijtenen, 1989).

However, Schumann (1973) and Larson (1962) offer a simple explanation on the effect of site and stand characteristics in ring porous woods, stating that good quality sites produce superior wood while faster growth results in enhanced properties. Zhaner (1968) and Zobel van Buijtenen (1989) offered a similar conclusion noting that wood properties in ring porous woods are strongly influenced by stand characteristics due to the varying conditions and the resulting affect on latewood production. As discussed previously, latewood production varies from year to year and is largely responsible for variation in wood properties.

Soil is a major component of site characteristics and thus wood properties often change with varying soil characteristics (Hamilton and Knauss, 1986; Koehler, 1933; Zobel and van Buijtenen, 1989). It is well accepted in studies of *Juglans nigra* L. that soil characteristics affect heartwood colour and size (Hiller *et al.,* 1972; Nelson *et al.,* 1969). Soils are also shown to alter composition and structure of cells in various ring porous woods (Hamilton *et al.,* 1978; Hamilton and Knauss, 1986; Zobel and van Buijtenen, 1989). Most importantly, soil characteristics are thought to influence density in many species (Hamilton *et al.,* 1978; Hamilton and Knauss, 1986; Wilde and Paul, 1959; Zhaner, 1968). However, variations in soil characteristics occur mostly over large geographic areas and are less important over smaller localized areas (Zobel and van Buijtenen, 1989).

The moisture regime present on a site can significantly influence growth patterns and result in changes in wood properties (Zobel and van Buijtenen, 1989). Several authors note that moisture may be the most important environmental factor affecting wood properties (Paul, 1959; Zobel and van Buijtenen, 1989). It is thought that increased moisture can prolong growth and increase desirable latewood percentages (Hildebrandt, 1960; Howe, 1970; Paul, 1959; Savill and Kanowski, 1993). This is confirmed by Benedict and Frelich (2008) who reported a positive impact from increased moisture on ring width, where as decreased or excessive moisture resulted in decreasing ring widths.

Silviculture

Silviculture is a form of environmental influence and is utilized in an attempt to control tree growth and form, which in turn, affects properties, characteristics and quality (Bendtsen, 1978; Cutter *et al.,* 2004; Hildebrandt, 1960; Jozsa and Middleton, 1994; Larson, 1962; Pliura *et al.,* 2006; Zobel, 1984). Common silviculture practices include fertilization, irrigation, thinning, pruning, stocking and vegetation control (Bendtsen, 1978; Cutter *et al.,* 2004; Jozsa and Middleton, 1994; Zobel, 1992; Zobel and van Buijtenen, 1989).

The influence on wood properties of some silviculture treatments is well known, while the effect of others is poorly understood (Hildebrandt, 1960; Zobel and van Buijtenen, 1989).

Zobel (1992) further states the effects of silvicultural treatments within the same stand may produce desired results in one tree but the opposite in another, as has been noted by others (Hildebrandt, 1960; Panshin and deZeeuw, 1980). Larson (1967) and Hildebrandt (1960) noted that large within tree variations often mask the effects of silvicultural activities.

Zobel and van Buijtenen (1989) and Hildebrandt (1960) state that it is difficult to make accurate generalizations to the effect of silviculture on wood properties. The literature on many aspects of the subject is immense but also largely contradictory (Bendtsen, 1978; Megraw, 1985; Zobel and van Buijtenen, 1989). All that can be said for certain is that silvicultural treatments alter the growth pattern and form of trees, thus there may be subsequent changes in wood properties within (Bendtsen, 1978; Jozsa and Middleton, 1994; Zobel and van Buijtenen, 1989; Zobel 1992).

Stand density control, via thinning or initial spacing, is a significant tool used in the management of forest stands and has significant influence on wood properties (Bendtsen, 1978; Bethune, 1968; Jozsa and Middleton, 1994; Kellison *et al.,* 1983; Larson, 1969; Sonderman, 1986; Zobel and van Buijtenen, 1989). It is thought to dramatically affect wood properties by altering growth rate, tree form and crown development (Bendtsen, 1978; Brazier, 1985; Carmean, 1973; Kellison *et al.,* 1983; Larson, 1969; Zobel, 1992). For example, thinning results in increased crown size, extensive root development, smaller defect cores, and most importantly, increased radial diameters (Brazier, 1985; Carmean, 1973; Erdmann *et al.,* 1975; Jozsa and Middleton, 1994; Landt and Phares, 1973; Larson, 1969; Paul, 1963; Phelps and Workmen, 1992; Sonderman, 1986). However, thinning can also lead to epicormic branching, larger branch sizes and excessive forking (Carmean, 1973; Cutter *et al.,* 2004; Landt and Phares, 1973;

Roberge, 1975; Sonderman, 1986; Zobel, 1992). Wider spaced trees are shown to have increased taper, greater height to diameter ratios, larger juvenile cores, and delayed onset of mature wood (Bendtsen, 1978; Cutter *et al.,* 2004; Erdmann *et al.,* 1975; Jozsa and Middleton, 1994; Larson, 1969; Pliura *et al.,* 2006; Sonderman, 1986; Zobel, 1992).

Competing vegetation control is common throughout Northwestern Ontario and is accepted practice in the establishment of desired species (Cutter *et al.,* 2004). Requirements for vegetation control during initial growth are well documented in many hardwoods (Schlesinger and Funk, 1977; Schlesinger and Van Sambeek, 1986; Van Sambeek *et al.,* 1989). However, the need for further vegetation control in later stages is less well known (Cutter *et al.,* 2004). Competing vegetation in the form of trees is resolved through thinning practices, while shrub or ground cover is reduced utilizing chemical or mechanical means (Cutter *et al.,* 2004). Failure to control competing vegetation is detrimental to wood properties by reducing growth and volume of desirable trees (Willcocks and Bell, 1995).

Pruning of small branches at low heights on the tree is often utilized in high value stands in an effort to improve wood quality and reduce defects (Cutter *et al.,* 2004; Jozsa and Middleton, 1994; Zobel and van Buijtenen, 1989; Zobel, 1992). This is accomplished by restricting branch stubs and the associated tension wood to smaller sections within the core of the tree (Carmean and Boyce, 1973; Kellison *et al.,* 1983; Larson, 1969). Further, Megraw (1985) noted that pruning can result in the production of mature wood more quickly in *Pinus spp*. Carmean and Boyce (1973) suggested that pruning, similar to thinning, would result in accelerated growth and larger diameters. However, improper pruning is common and can negate the positive benefits, resulting in poor quality, increased disease, and marginal growth (Cutter *et al.,* 2004; Grisez, 1978; Zobel, 1992; Zobel and van Buijtenen, 1989).

An understanding of proper rotation age is the most effective means to influence wood quality utilizing silvicultural practices (van Buijtenen, 1969; Zobel, 1984). Younger trees have increased amounts of juvenile wood, which is inferior in properties and quality to mature wood (Bendtsen, 1978; van Buijtenen, 1969). However, diameter growth slows past a certain age and the production of new wood material is negligible (Bendtsen, 1978). Older trees are also more susceptible to disease, injury and pest attack (Zobel, 1984).

SPECIES DESCRIPTION

Black ash occurs naturally throughout Northeastern North America from Atlantic Canada, west to Southeastern Manitoba and South to Iowa and Virginia and East to the Eastern Seaboard (Figure 14) (Benedict and David, 2000; Cassens, 2007; Wright and Rauscher, 1990). It is the major hardwood species on lowlands in the northern Lake States of the United States and is also common throughout Northwestern Ontario with the highest concentrations found in the Southwestern districts (Ontario Ministry of Natural Resources, 2011; Weber *et al.,* 2007).

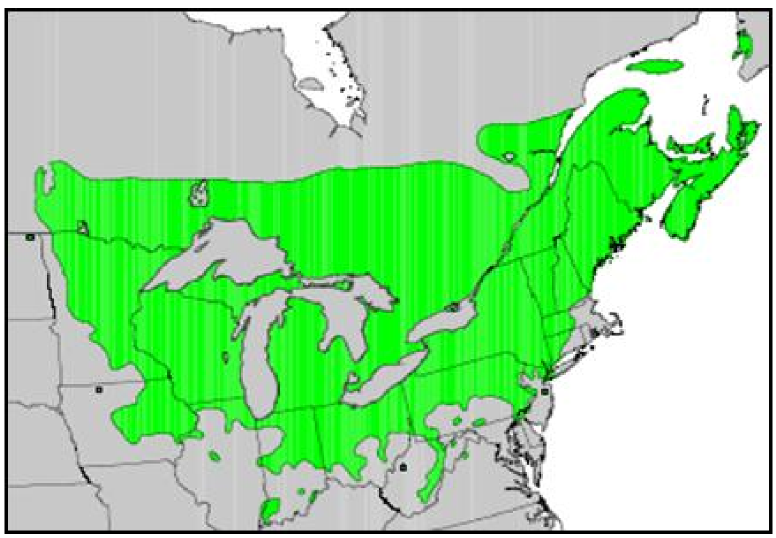

Figure 14. Range of Black ash across North America (Wright and Rauscher 1990).

Black ash commonly occurs on wetland sites throughout its range (Benedict and Frelich, 2008; Erdmann *et al.,* 2008; Wright and Rauscher, 1990). Bogs, fens, stream banks, and poorly drained, seasonally flooded areas are common sites for black ash growth (Benedict and David, 2000; Diamond and Emery, 2011; Erdmann *et al.,* 2008; Tardiff and Bergeron, 1999; Weber *et al.,* 2007). Soil composition on these sites ranges from moist to wet muck or peat soils to fine sands or sandy loams (Benedict and David, 2000; Erdmann *et al.,* 2008; Wright and Rauscher, 1990). Table 4 displays the designated site classifications for black ash growth in Ontario and the United States.

Black ash is tolerant of semi-stagnant water conditions and has adapted to the reduced oxygen content associated with these wet locations (Tardiff and Bergeron, 1999; Weber *et al.,* 2007; Wright and Rauscher, 1990). However, it is important that the water remain moving as to allow the soil to remain aerated (Wright and Rauscher, 1990). Black ash is less tolerant to flooding for prolonged periods well into the growing season. Massive dieback of vegetation on sites prone to prolonged flooding is frequent on lowland sites (Tardiff and Bergeron, 1999; Weber *et al.,* 2007).

Table 4. Designated site classification for black ash growth in Ontario and the United States

	American Classification		Ontario Classification
Type	Major Component	Type	Major Component
39	Black Ash-American elm- Red Maple	30	Black Ash Hardwood: Fresh, Silty-Clayey Soil
37	Northern White-Cedar	37	Rich Swamp: Cedar: Organic Soil
		38	Rich Swamp: Black Ash: Organic-Mineral Soil
	Minor Component		Minor Component
5	Balsam Fir	17	White Cedar: Fresh-Moist, Coarse-Fine Loamy Soil
12	Black Spruce	19	Hardwood-Fir-Spruce : Fresh, Sandy-Coarse Loamy Soil
24	Hemlock-Yellow Birch	23	Hardwood-Fir-Spruce : Moist, Sandy-Coarse Loamy Soil
38	Tamarack	32	Fir-Spruce Mixedwood: Moist, Silty-Clayey Soil
		33	Hardwood-Fir-Spruce : Moist, Silty-Clayey Soil

Source: (Eyre, 1980; Racey *et al.,* 1996; Stewart and Krajicek, 1978; Weber *et al.,* 2007)

Little is understood on black ash growth and available literature is limited (Stewart and Krajicek, 1978; Tardiff and Bergeron, 1999). Wright and Rauscher (1990) suggest that growth of black ash is generally slower than associate species and is compounded by the presence of high water tables on commonly occupied sites. This was confirmed by Erdmann *et al.,* (2008) and Carmean (1979) who suggest extremely slow growth on organic peat and muck soils. However, Stewart and Krajicek (1978) state that similar to most species, black ash growth is optimum on fertile, moist, and well drained sites. Carmean (1979) suggested that black ash has rapid early height growth, followed by a pronounced slowing of height growth past age 50.

Benedict and Frelich (2008) explain that it is frequently assumed that lowland sites are ideal for black ash growth given that the species is most often associated with these locations. However, these sites are often not ideal growing conditions for high quality wood. High competition, shallow rooting depth and frequent disturbance limit the growth potential on these sites (Benedict and Frelich, 2008; Erdmann *et al.,* 2008). Keeland *et al.,* (1987) and Benedict and Frelich (2008) suggest that black ash growth would be much more productive on drier sites. Similar to other species frequently found in lowland sites, black ash likely occurs in these areas as it is one of the few species that can successfully grow under the challenging conditions (Benedict and Frelich, 2008). Yet, if it were established on upland sites, would grow more productively (Benedict and Frelich, 2008).

It is assumed that growth is limited on upland sites due to increased competition. Black ash has a more difficult time becoming established on these sites and is often outcompeted by other tree species and forest vegetation (Benedict and Frelich, 2008). However, Carmean (1979) noted that black ash growth is faster than associate species on well-drained soils. In a comparison of site indices of black ash to *Betula alleghaniensis* Britt., *Fraxinus americana* L. and *Ulmus Americana* L., black ash indices were more than 5 feet greater on similar upland sites.

Black ash is frequently described within the literature as a short lived species, with an average age of approximately 75 years. Parker and Schneider (1974) found the oldest tree in their research to be 69 years old. However, more recent research indicates the species to be significantly longer lived. Tardiff and Bergeron (1999) consistently measured trees over 200 years of age in their extensive study of black ash in Northern Quebec. The oldest tree had an age of 319 years. Erdmann *et al.,* (1987) reported trees as old as 241 years in Wisconsin while Benedict and Frelich (2008) reported trees older than 300 years as common throughout northern Minnesota.

Wright and Rauscher (1990) and Diamond and Emery (2011) state that black ash is generally a small tree, however, further literature indicates that growth of black ash is largely dictated by site characteristics. Erdmann *et al.,* (1987) reported that trees grown on better quality sites reach heights of 65 to 70 feet and diameters of 18 inches at d.b.h. This was confirmed by Wright and Rauscher (1990) who indicate these values as “large trees”. They further suggest that more common diameters are 8 to 10 inches d.b.h. Erdmann *et al.,* (1987) reported slower growth on organic peats and mucks with heights of 50 to 60 feet and diameters of 10 to 12 inches d.b.h. Clermont and Schwartz (1952) reported black ash in Eastern Ontario to be 73 to 85 feet in height with a diameter of 11 to 19 inches d.b.h.

Wood Characteristics

Black ash is classified as ring porous, as the vessels formed earlier in the season are much larger than those formed later in the year (Bowyer *et al.,* 2003; Desch and Dinwoodie, 1996, 1981; Hoadley, 2000; Panshin and de Zeeuw, 1980; Tsoumis, 1991). The large earlywood vessels are distinctly oval and seen as bands of two to four multiples within the early wood of the growth ring (Forest Products Laboratory, 1919; Hoadley, 1990; Panshin and de Zeeuw, 1980). The vessels within the latewood are much smaller and form similar bands of two to four or frequently as solitary vessels (Panshin and de Zeeuw, 1980). The latewood vessels are also surrounded by sheaths of light coloured parenchyma cells (Hoadley, 1990). Fibres constitute nearly 70 percent of the total cell volume in black ash. The transition from earlywood to latewood within a growth ring of black ash is abrupt and distinct (Cassens, 2007; Hoadley, 1990; Keith and Kellogg, 1981; Panshin and de Zeeuw, 1980; Stewart and Krajicek, 1978).

The heartwood of black ash is distinctly reddish to grayish brown in colour and contrasts greatly with the light coloured sapwood (Alden, 1994; Burns and Honkala, 1990; Perem *et al.,* 1981; Stewart and Krajicek, 1978). However, as discussed above, the relative size of the heartwood can vary greatly within the species. Stewart and Krajicek (1978) suggest sapwood widths of three to six inches in width while most others authors agree it rarely exceeds one inch in width (Forest Products Laboratory, 1919; Hoadley, 1990; Sterrett, 1917). The heartwood is generally thought of as only slightly durable to decay and fungal attack (Alden, 1994; Burns and Honkala, 1990; Hoadley, 1990; Wang and DeGroot, 1996).

Utilization

It is difficult to characterize the characteristics of black ash wood given its high degree of variability. However, it is thought to be inferior in properties to the more abundant white ash (Alden, 1994). It has lower strength, lower density and is less desirable for machining and workability (Alden, 1994). However, black ash wood ranks favourably when compared to other native hardwoods and is inexpensive and largely underutilized (Alden, 1994).

Black ash wood is still generally thought to be heavy and hard with a high shock resistance (Perem *et al.,* 1981). It wears smoothly and is above average in machining properties (Alden, 1994; Perem *et al.,* 1981). It has a high nail holding capacity though does have a tendency to split (Perem *et al.,* 1981). Gluing can also be difficult given the porous and textured wood surface (Alden, 1994; Perem *et al.,* 1981). The wood is unique in that it bends readily and easily (Perem *et al.,* 1981). In drying, it seasons well and has only moderate defect rates and incurs little shrinkage (Perem *et al.,* 1981).

The wood is utilized exclusively in secondary products (Cassens, 2007). The best grades are developed for tool handles, furniture, mill-work, interior trim, and cabinetwork. The more pronounced grain and features of black ash make it an increasingly popular choice for flooring, novelty products and woodworking projects (Perem *et al.,* 1981; Wiemann, 2010). Black ash is still utilized today as the primary source for traditional basket-making (Panshin and de Zeeuw, 1980; Wright and Rauscher, 1990). The current primary and historical uses for black ash are displayed in Table 5.

Table 5. Utilization of black ash in manufacturing.

Primary Utilization	Historical Utilization
Upholstered furniture	Butter churns
Furniture	Vehicle components
Flooring	Refrigerators
Ceiling, siding and stairs	Pumps and rods
Window and door frames	Toys
Cabinet work	Machine components
Trim and molding	Elevators
Tool Handles	Airplane Industry
Sporting goods	
Boxes, crates and pallets	
Woodenware and novelties	
Basketmaking	

Source: (Alden, 1994; Perem *et al.,* 1981; Sterrett, 1917; Wiemann, 2010)

METHODOLOGY

EXPERIMENTAL DESIGN

Wood properties in differing radial and longitudinal positions were measured and recorded in nine mature black ash stems grown within the Thunder Bay seed zone as designated by the Ontario Ministry of Natural Resources (Figure 15). Longitudinal positions reflect 0, 25, 50 and 75 percent of total merchantable height. Radial positions reflect the juvenile wood core, transition zone and mature wood of each stem categorized by the test specimen location in relation to the pith. Measured wood properties include MOE, MOR, compression parallel to the grain, Janka ball side hardness, relative density, ring width, latewood percentage and average ring density.

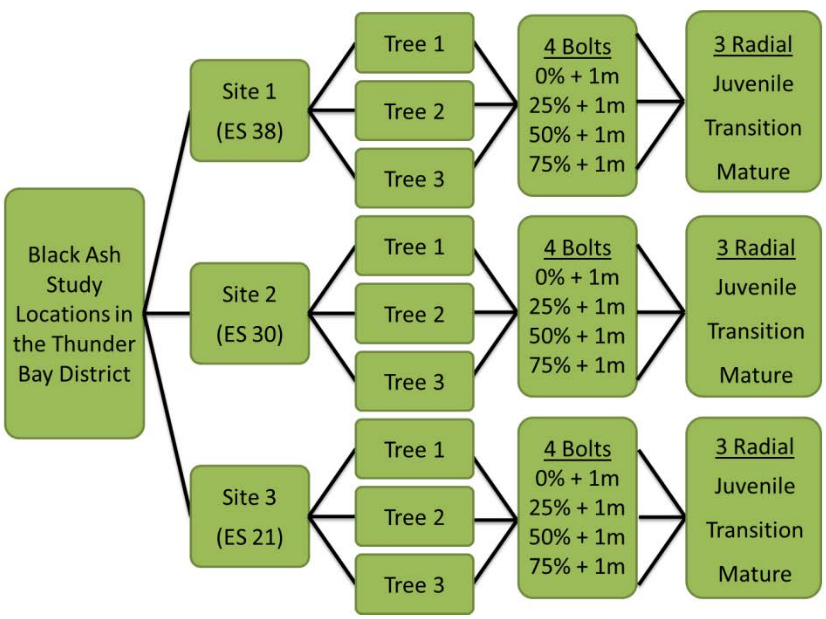

Figure 15. Experimental design of wood property tests.

FIELD PROCEDURES

Site Selection

Three sites composed of mature black ash trees were selected for sampling within the Thunder Bay Seed Zone. Two sites were selected near Heart Lake, 130 kilometres West of Thunder Bay, in the Dog River Matawin Sustainable Forest License (SFL). Another site was located on Belluz Farms, 30 kilometres Southwest of Thunder Bay within the Lakehead SFL (Figure 16). Sample collection occurred in the spring of 2010.

Figure 16. Location of sample sites.

Stand selection was concentrated in areas consisting of black ash as a major stand component and focused on providing an accurate representation of potential growth across the seed zone. In addition, stands were selected based on the quality and quantity of potential samples within the stand (Figure 17). All stands were unique in their site characteristics and species composition as defined by ecosites in the Terrestrial and Wetland Ecosites of Northwestern Ontario (Racey *et al.,* 1996), including:

- Site 1: Ecosite 38 – Rich Swamp, Black Ash (Other Hardwood); Organic Mineral Soil; rich, forested wetland dominated by black ash, seasonally flooded with a high water table

- Site 2: Ecosite 23 – Hardwood, Fir, Spruce, Mixedwood; Moist, Sandy Coarse Loamy Soil; rich, mixedwood forest dominated by upland deciduous species, found on low slopes and rolling terrain

- Site 3: Ecosite 30 – Black Ash Hardwood; Fresh, Silty Clayey soil; well drained sites dominated by black ash with occurrences of other broadleaves

Figure 17. Sample locations, site one, two and three, respectively.

<u>Tree Selection</u>

Three mature trees from each stand were selected for destructive sampling based on a number of criteria identified to ensure quality, quantity and reliability of sample data. Dominant or co-dominant trees in the over-story were visually examined by the field collection team to ensure that no visible defects or diseases were present that could potentially affect sample quality. Trees were required to be of sufficient diameter to ensure an adequate sample size and the guaranteed presence of mature wood within the stem, defined as greater than 30 years of age.

It was also required that trees be of excellent form and vigour; displaying little excess branching, no crooks, splits or seams as well as minimal lean.

Trees selected based on the above criteria were felled and destructively sampled for mechanical and physical property testing. Tree characteristics and applicable measurements were recorded for each tree as per the American Society for Testing and Materials (ASTM) Standard Practice for Sampling Forest Trees for Determination of Clear Wood Properties (D5536-94) (2010) as well as the Ontario Forest Growth and Yield Program Field Manual for Establishing and Measuring Permanent Sample Plots (Hayden *et al.,* 1955).

The location of sample bolts was determined based on the total merchantable height of the stem, defined as the height to a 10 centimetre diameter or significant stem fork. Four bolts, one metre in length were collected from all trees at 0, 25, 50 and 75 percent of merchantable height (Figure 18). Bolts were correctly labelled and returned to the Lakehead University Wood Science and Testing Facility (LUWSTF) for sample preparation and analysis.

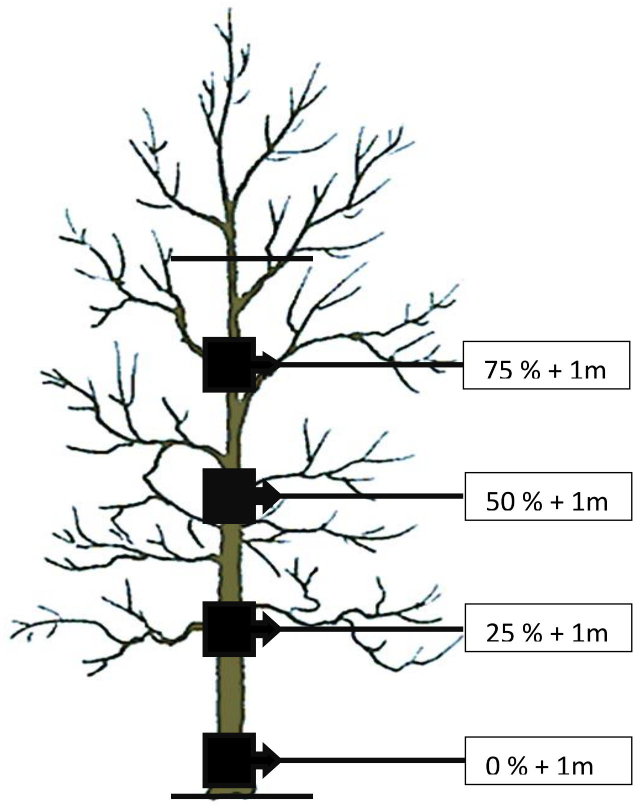

Figure 18. Location of sample bolts in selected trees.

LABORATORY PROCEDURES

Sample Preparation

Mechanical and Physical Properties

Collected samples were sawn into three centimetre longitudinal slabs utilizing a Woodmizer LT40 Portable Hydraulic Band Sawmill. Sawn slabs were then trimmed to 55 centimetre lengths based on potential for sample quality and air dried to below 30 percent moisture content. Moisture content was determined using a GE Protimeter Surveymaster moisture meter.

Once below 30 percent moisture content, the slabs were divided into 15 centimetre samples to be utilized in side hardness testing and 40 centimetre samples for MOE, relative density and compression parallel to the grain tests. The 40 centimetre slabs were sawn into 2.5 by 2.5 by 40.0 centimetre test samples and all samples were further air dried to 15 percent moisture content.

Once the MOE samples reached the desired 15 percent moisture content, they were further processed to 2.0 x 2.0 x 40.0 centimetre samples and placed in the Thermo Scientific Environmental Chamber. All samples were left to stabilize to 12 percent moisture content in the chamber, which was set at 20 degrees Celsius and 60 percent relative humidity.

Upon reaching the desired 12 percent moisture content, samples were further trimmed to 2.0 x 2.0 x 30.0 centimetre MOE test samples, 2.0 x 2.0 x 6.0 cm compression parallel to the grain samples, and 2.0 x 2.0 x 3.0 centimetre relative density samples. During the final preparation and trimming process, samples were culled to ensure only proper, straight grained and defect-free samples were analyzed.

To ensure continuity of sample arrangement and proper test potential, samples were continually labelled to reflect the site number, tree number, longitudinal position, radial position, and cardinal direction; North, South, East, or West.

<u>X-Ray Densitometry Samples</u>

Cross sectional discs, one inch in thickness, were collected from each longitudinal distance and were processed for analysis in the Quintex Measurement Systems (QMS) Direct Scanning X-ray densitometer. Discs were air dried to below 30 percent moisture content and processed in a three-step process. First, using a bandsaw, discs were sawn in half along a North-South radius. The section was then sanded on both faces to ensure a smooth and clean surface. A standard table saw was utilized to remove a two millimetre sample from each section. Careful attention to detail in the sawing procedures was used to ensure the pith was centralized within each sample and minimal variation in width existed along the entire length. The processed samples were then placed in Thermo Scientific Environmental Chamber to ensure consistent moisture contents of 12 percent. No extractive removal was performed on the samples.

Testing Procedures

Mechanical and Physical Properties

Sampling procedure was conducted in accordance with ASTM Standard Practice for Sampling Forest Trees for Determination of Clear Wood Properties (D5536-94) (2010). However, it was found that the ASTM standard limits potential samples through inclusion of the pith within samples, as well testing is limited to a maximum of eight samples per radial position. Sampling of trees from the Thunder Bay region suggests that removal of clear wood samples may limit study validity and create insufficient sample numbers.

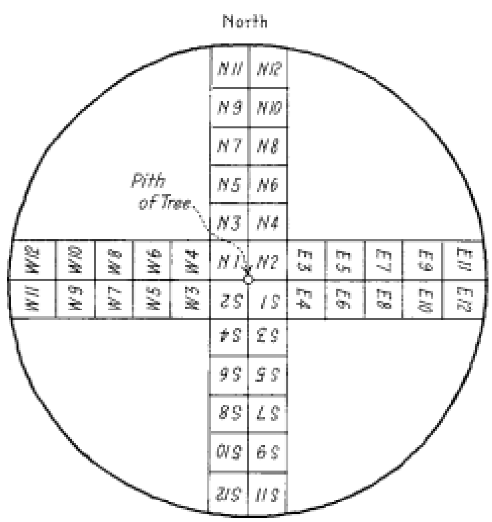

Figure 19. ASTM standards testing procedure with included pith samples (ASTM, 2010)

The LUWSTF has created a modified testing procedure to ensure accuracy and viability of sample testing. Radial test samples were increased in numbers and positioned to avoid pith in potential samples. If the target eight samples in each radial position were unavailable, samples were recovered from the next nearest sample.

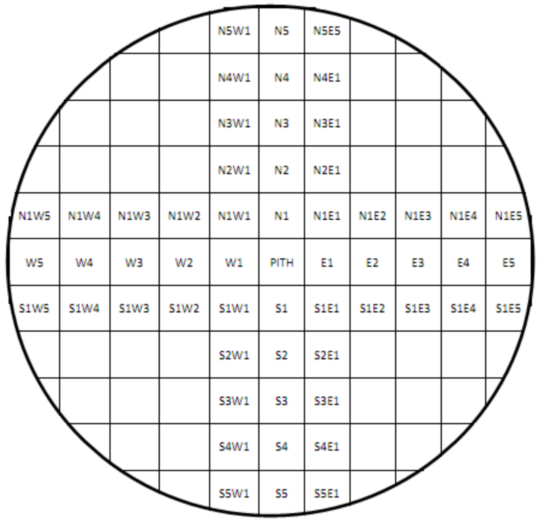

Figure 20. LUWSTF modified test procedure.

Tinius Olsen H10KT and H50KT Universal Wood Testing Machines, with Test Navigator software, were used to determine mechanical properties, including:

- MOE; reported in mega pascals (MPa) utilizing the three point flexure test procedure with a maximum span of 24 centimetres.
- MOR; reported in MPa, based on the maximum load (Newtons) reported during MOE testing
- Compression parallel to the grain; reported in MPa, utilizing the compression parallel to grain tool
- Side hardness; reported in Newtons (N) using the Janka Ball tool

Tests were conducted in accordance with ASTM Standard Test Methods for Small Clear Specimens of Timber (D143 – 09) (2009) and Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials (D4442 – 07) (2007).

Relative density for each sample was determined using Method B - Volume by Water Immersion methodology found in the ASTM Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials (D 2395 – 07a) (2007). Relative density samples were weighed at 12 percent moisture content and again at oven dry moisture content.

Juvenile Core

Following mechanical property testing, samples were organized to reflect the juvenile core within the stem, as designated by the first sample distance from the pith. The juvenile core represents a consistent area unaffected by the juvenile and mature wood transition. Juvenile core mechanical properties examined included those demonstrating significant results in whole tree testing; MOE, compression parallel to the grain and side hardness.

X-Ray Densitometry Samples

Density, ring width and latewood percentage were determined on the prepared cross-sectional samples using a QMS QTRS-01X Tree Ring Analyzer. The QMS system produces an

X-ray beam of 17.5 kilo-electron volts generated by a matched high voltage power supply. The X-ray beam is passed through a narrow slit, known as a collimator to provide a concentrated beam of X-ray radiation. The standard collimator utilized measures 0.0038cm x 0.159cm.

Prior to scanning, all samples were measured using digital callipers to record total length and sample thickness, which was entered into the sample parameters window. Target densities and resulting mass absorption coefficients were set based on density information recorded for each sample height. The threshold method, which makes assumptions on the presence of early wood or latewood based on a predetermined density threshold, was utilized to determine the latewood percentage and resulting ring locations. A representative threshold value for each sample tree was determined, values ranged from 450 to 600 kg/m^3. The QMS system provides a detailed summary of values for each ring based on the locations determined using the threshold method. Average values for each radial distance were determined based on the calculated distance from the pith corresponding to the small clear specimens utilized in mechanical property testing.

STATISTICAL ANALYSIS

Variation in Properties

The objective of this study was to determine if a significant difference in properties existed within trees both radially and longitudinally. The null hypothesis stated that;

H_1 - radial position within the tree will have no effect on properties

H_2 - longitudinal position within the tree will have no effect on properties

H_3 - geographic location of the tree will have no effect on wood properties.

To address the objectives of the study and test the stated null hypotheses, analysis of variance (ANOVA) tests were carried out with a general linear model at 95 percent confidence using the Statistical Program for Social Sciences (SPSS) 19.0 software. Interactions were pooled when no significance was determined and Duncan's post hoc test was utilized to identify statistically similar values.

ANOVA models allow variation to be attributed to a given factor within the model and thus determine if there is significant variation among factor means and to what level of significance (DeVeaux *et al.,* 2008; Howell, 2002; Norton and Strube, 1985). Probability values within the ANOVA Table indicate the likelihood of error in the assumption that there is variation in the levels of the factors tested. A probability of 5 percent (0.05) or less is considered statistically significant (DeVeaux *et al.,* 2008; Norton and Strube, 1985). The ANOVA model operates on the basis three main assumptions;

1. The independence assumption states that the groups must be independent, both within and between samples.

2. The equal variance assumption states that variances of the treatment groups must be homogenous

3. The normality assumption states the errors must be normally distributed.

(DeVeaux *et al.,* 2008; Howell, 2002).

The linear models states that each observation is the sum of the population mean in addition to the variation owing to the relevant factors; including replications as well as a measure of sampling error (Norton and Strube, 1985). The model includes the components radial position, longitudinal position, site and tree, which is nested in site. Factors tree, radial position and longitudinal position are fixed while site is random. The experimental unit is the mean value of the measured property of each radial distance within the tree. The linear model for this experiment is presented in Equation 1.

$$Y_{ijkl} = \mu + S_i + T_{(i)j} + L_k + R_l + SL_{ik} + SR_{il} + TL_{(i)jk} + TR_{(i)jl} + SLR_{jlk} + TLR_{(i)jkl} + \varepsilon_{(ijkl)} \quad [1]$$

i = 1,2,3; j = 1,2,3; k = 1,2,3,4; l=1,2,3

Where,

Y_{ijkl} = The measured response of the k^{th} longitudinal distance and the l^{th} radial distance within the j^{th} tree from the i^{th} site.
μ = the overall mean.
S_i= the random effect of the i^{th} site
$T_{(i)j}$= the fixed effect of the j^{th} tree, within the i^{th} site
L_k = the fixed effect of the k^{th} longitudinal position.
R_l = the fixed effect of the l^{th} radial position.
SL_{ik} = the mixed effect of the i^{th} site with the k^{th} longitudinal position
SR_{il} = the mixed effect of the i^{th} site with the l^{th} radial position
$TL_{(i)jk}$ = the mixed effect of the j^{th} tree with the k^{th} longitudinal position
$TR_{(i)jl}$ = the mixed effect of the j^{th} tree with the l^{th} radial position
SLR_{ikl} = the mixed effect of the i^{th} site with the k^{th} longitudinal position and the l^{th} radial position
$TLR_{(i)jkl}$ = the mixed effect of the j^{th} tree with the k^{th} longitudinal position and the l^{th} radial position
$\varepsilon_{(ijkl)}$ = the random effect of the k^{th} longitudinal distance and the l^{th} radial distance within the j^{th} tree from the i^{th} site.

The expected mean squares associated with Equation 1 are presented in Table 6. Hypotheses tests for Equation 1 are displayed in

Table 7. Direct tests were available for factors site, radial position, and longitudinal position and simultaneously for the radial and longitudinal position interactions.

Table 6. Expected mean square derivation for Equation 1.

	3	3	4	3		
	R	F	F	F		
Source	i	j	k	l	Expected Mean Squares	df
S_i	1	4	4	3	$\sigma^2 + 12\phi_{(T)} + 48\sigma_S^2$	2
$T_{(i)j}$	1	0	4	3	$\sigma2 + 12\phi_{(T)}$	6
L_k	3	4	0	3	$\sigma2 + 12\sigma_{SL}^2 + 36\sigma_L^2$	3
R_l	3	4	4	0	$\sigma^2 + 12\sigma_{SR}^2 + 48\sigma_R^2$	2
LR_{kl}	3	4	0	0	$\sigma2 + 4\phi_{(SLR)} + 12\ \phi_{LR}$	6
SL_{ik}	1	4	0	3	$\sigma2 + 12\sigma_{SL}^2$	6
SR_{il}	1	3	4	0	$\sigma^2 + 12\sigma_{SR}^2$	4
$TR_{(i)jl}$	1	0	4	0	$\sigma^2 + 4\phi_{(TR)}$	12
$TL_{(i)jk}$	1	0	0	3	$\sigma^2 + 3\phi_{(TL)}$	18
SLR_{ikl}	1	4	0	0	$\sigma^2 + 4\phi_{(SLR)}$	12
$TLR_{(i)jkl}$	1	0	0	0	σ^2	36
$\varepsilon_{(ijkl)}$	1	1	1	1	σ^2	0

Table 7. Hypotheses tests for linear model in Equation 1.

Hypothesis	Test Statistic	Reference Distribution
$\sigma_S^2 = 0$	MS(S)/MS(T)	F(2,6)
$\sigma_T^2 = 0$	-	-
$\sigma_L^2 = 0$	MS(L)/MS(SL)	F(3,6)
$\sigma_R^2 = 0$	MS(R)/MS(SR)	F(2,2)
$\sigma_{LR}^2 = 0$	MS(LR)/MS(SLR)	F(6,12)
$\sigma_{SL}^2 = 0$	-	-
$\sigma_{SR}^2 = 0$	-	-
$\sigma_{TL}^2 = 0$	-	-

$\sigma_{TR}^2 = 0$	-	-
$\sigma_{(SLR)} = 0$	-	-
$\phi_{(TLR)} = 0$	-	-

Predicting Mechanical Properties

The relationship between relative $density_{12}$ and measured mechanical properties; MOE, MOR, compression parallel to the grain and side hardness were investigated using linear, logarithmic and exponential equations developed in SPSS 19.0 software. Regression analysis was compared using coefficients of determination to establish if the variation in mechanical properties due to relative $density_{12}$ could be explained via the above regression equations. It was hypothesised that the linear function best represents the relationship between relative $density_{12}$ and measured mechanical properties.

Regression assumptions were tested using the Shapiro-Wilks test of normality while predicted values were plotted against residual values to test for normality and homogeneity of variance, respectively, for each regression analysis.

The null hypothesis for all models states that the slope of the model is equal to zero, and that there is no relationship between relative $density_{12}$ and the measured mechanical property. Each regression equation was tested to determine if the relationship between relative density and measured mechanical properties was significant at 95 percent confidence.

R^2 is a measure of the variance accounted for by the selected data and is a reliable indicator of goodness of fit. R^2 is defined as the square of the sample correlation coefficient between the outcomes and their predicted values (DeVeaux *et al.,* 2008).

Exponential equations developed by the United States Department of Agriculture (USDA) Forest Products Laboratory (FPL) which utilize relative denisty$_{12}$ to predict mechanical properties in hardwoods (Table 8) were examined in relation to collect data.

Table 8. Functions relating measured mechanical properties to relative density (x).

Measured Property	Relative Density$_{12}$ - Strength Relationship
MOE(kPa)	$= 16\,500\ x^{0.07}$
MOR(MPa)	$= 171\,300\ x^{1.13}$
Compression (kPa)	$= 76\,000\ x^{0.89}$
Side Hardness (N)	$= 15\,300\ x^{2.09}$

Source: (Kretschmann, 2010).

RESULTS

Table 9 displays the mean wood properties of each sample site, grand means of the entire study and published values reported within the literature. The third site, the well-drained site displays the largest mean values in nearly all tests, followed closely by the second site, the upland site. The first site, the lowland swamp, consistently displayed the lowest mean values across all tests. Much variation was also observed between study means and those reported within the literature.

Table 9. Mean values from the Thunder Bay seed zone and available published data.

Measured Property	Site			All Sites	Jessome (1977)	Markwardt and Wilson (1935)
	1	2	3			
$Density_{12}$ (Kg/m^3)	625	660	670	652	-	-
Relative $Density_{12}$	557	591	582	577	494	490
Relative $Density_{OD}$	591	630	623	614	539	530
MOE (MPa)	6855	8736	9691	8437	13500	11032
MOR (MPa)	77	91	97	88	84	87
Compression - Parallel(MPa)	36	46	39	41	41	41
Hardness - Side (N)	5182	5597	5738	5506	4220	3781
Ring $Density_{12}$ (Kg/m^3)	581	627	660	623	-	-
Ring Width (mm)	1.05	1.48	1.63	1.39	1.4	-
Latewood Percentage (%)	45	61	64	57	-	-

VARIANCE IN WHOLE TREE PROPERTIES

Relative Density and Density

Values of relative density$_{OD}$, relative density$_{12}$ and density$_{12}$ were analysed and are displayed in Table 10. The ANOVA results indicate that variation between sites was significant at 95 percent confidence, while variations between longitudinal and radial distances and interactions between factors were not significant at a 95 percent confidence level. Relative density$_{OD}$ mean values were larger than relative density$_{12}$, while desnity$_{12}$ had the highest values.

Table 10. ANOVA results for density and relative density.

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	Density$_{12}$	51546.907[a]	7	7363.844	3.620	.002
	Relative Density $_{OD}$	33160.861[b]	7	4737.266	2.065	.054
	Relative Density$_{12}$	27971.000[c]	7	3995.857	2.287	.033
Intercept	Density$_{12}$	45942533.333	1	45942533.333	22587.087	.000
	Relative Density $_{OD}$	40797885.565	1	40797885.565	17786.422	.000
	Relative Density$_{12}$	35977107.000	1	35977107.000	20594.122	.000
Radial	Density$_{12}$	7198.389	2	3599.194	1.770	.176
	Relative Density $_{OD}$	1450.463	2	725.231	.316	.730
	Relative Density$_{12}$	4624.222	2	2312.111	1.324	.271
Longitudinal	Density$_{12}$	3886.963	3	1295.654	.637	.593
	Relative Density $_{OD}$	517.880	3	172.627	.075	.973
	Relative Density$_{12}$	1142.111	3	380.704	.218	.884
Site	Density$_{12}$	40461.556	2	20230.778	9.946	.000
	Relative Density $_{OD}$	31192.519	2	15596.259	6.799	.002
	Relative Density$_{12}$	22204.667	2	11102.333	6.355	.003
Error	Density$_{12}$	203401.759	100	2034.018		
	Relative Density $_{OD}$	229376.574	100	2293.766		
	Relative Density$_{12}$	174696.000	100	1746.960		

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Total	$Density_{12}$	46197482.000	108			
	Relative Density $_{OD}$	41060423.000	108			
	Relative $Density_{12}$	36179774.000	108			
Corrected Total	$Density_{12}$	254948.667	107			
	Relative Density $_{OD}$	262537.435	107			
	Relative $Density_{12}$	202667.000	107			

a. R^2= .202 (Adjusted R^2= .146) b. R^2= .126 (Adjusted R^2= .065) c. R^2= .138 (Adjusted R^2= .078)

Relative $density_{OD}$ values varied between 524 kg/m^3 and 735 kg/m^3 with a grand mean of 614 kg/m^3. Figure 21 displays boxplot comparisons of relative $density_{OD}$ (kg/m^3) values by site. The third site, the well-drained site, produced the highest mean values at 623 kg/m^3 but also displayed the largest variance. The first site, the wetland site, produced the lowest mean values at 590 kg/m^3 and the smallest variance (Figure 21). The ANOVA revealed that variance between sites was significant at 95 percent confidence while radial and longitudinal position was not significant.

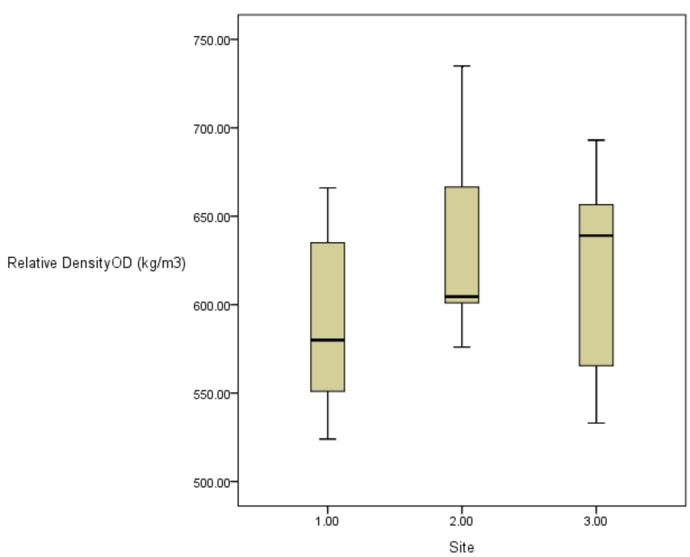

Figure 21. Boxplot comparison of relative $density_{12}$ (kg/m^3) values by site.

Relative $density_{12}$ values varied between 496 kg/m^3 and 676 kg/m^3 with a grand mean of 577 kg/m^3. Figure 22 displays relative $density_{OD}$ (kg/m^3) values by site. Again, the well-drained site produced the highest mean values at 582 kg/m^3, while the wetland site produced the lowest at 557 kg/m^3. The ANOVA revealed that variance between sites was significant at 95 percent confidence while radial and longitudinal positions were not significant.

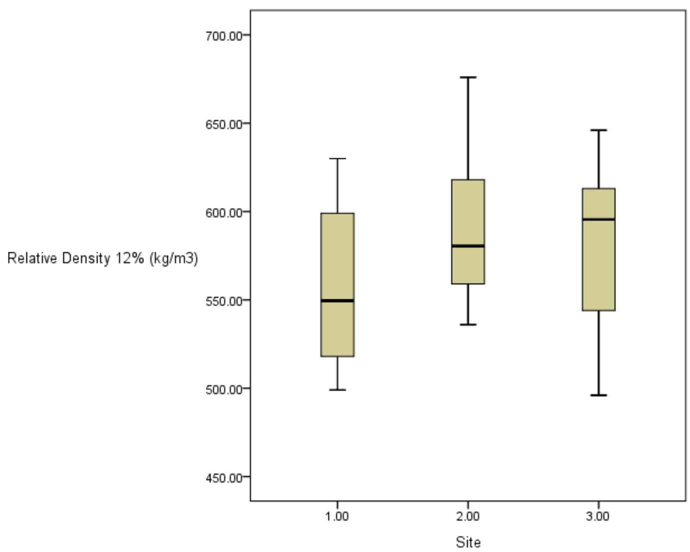

Figure 22. Comparison of relative $density_{OD}$ (kg/m^3) values by site.

$Density_{12}$ values varied between 561 kg/m^3 and 753 kg/m^3 with a grand mean of 652 kg/m^3. The well-drained site produced the largest mean values of $density_{12}$ at 670 kg/m^3 while the wetland site produced the lowest at 625 kg/m^3. The upland site produced mean values of 660 kg/m^3. The ANOVA results revealed that variance between sites was significant at a 95 percent confidence level while radial and longitudinal positions were not significant. Figure 23 compares $density_{12}$ (kg/m^3) values by site.

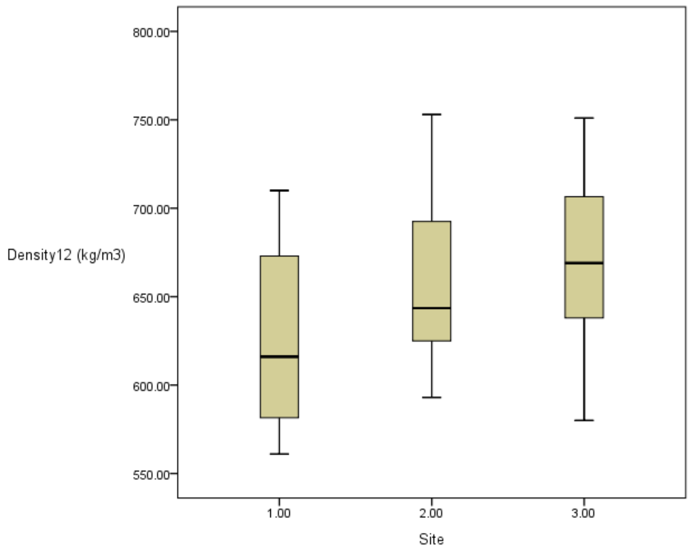

Figure 23. Comparison of $density_{12}$ (kg/m^3) values by site.

The ANOVA results revealed that patterns of radial variation of relative $density_{OD}$ and $_{12}$ and $density_{12}$ were not significant at 95 percent confidence, however, the values demonstrate a general pattern of radial decrease (Figure 24).

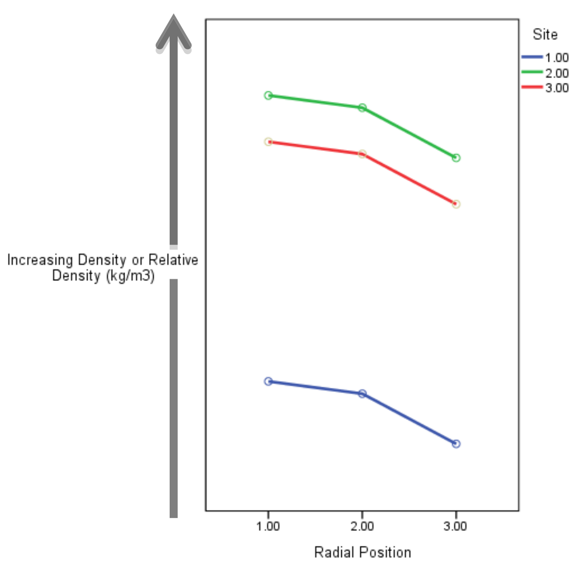

Figure 24. Radial variation of relative $density_{OD}$ and$_{12}$ and $density_{12}$ (kg/m^3) values by site

The ANOVA results also revealed patterns of longitudinal variation to be non-significant at 95 percent confidence, however, relative density$_{OD}$ and $_{12}$ and density$_{12}$ values followed a general pattern of increased values in the base, followed by a marginal decrease through the centre of tree and increasing towards the top (Figure 25).

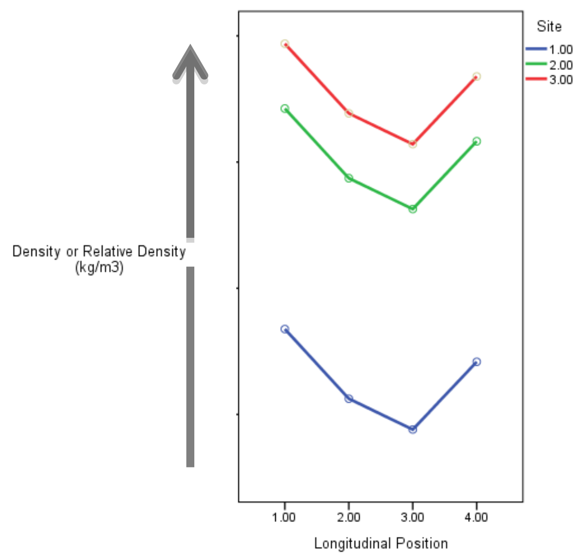

Figure 25. Longitudinal variation of relative density$_{OD}$ and$_{12}$ and density$_{12}$ (kg/m^3) values by site.

The ANOVA demonstrates that the null hypothesis of no variance in wood relative density or density means is rejected at 95 percent confidence. Significant variance was observed between sites while variance in radial and longitudinal positions was not significant.

A Duncan's post hoc test was performed on the relative density$_{OD}$ and $_{12}$ and density$_{12}$ mean values for sites (Figure 26). The test revealed two subsets of sites:

- Subset A; the first site, consisting of the lowland black ash swamp.
- Subset B: including the second and third site, the upland, and well-drained sites.

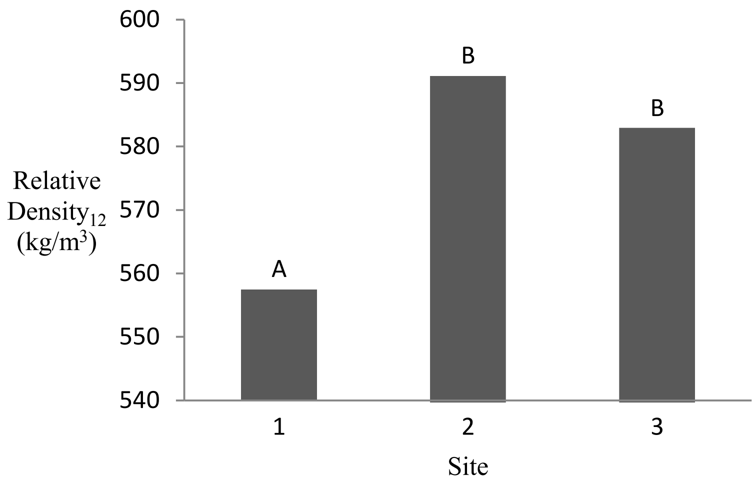

Figure 26. Post hoc test results for density and relative density (kg/m^3) values by site*.

* Similar letters indicate no significant difference.

<u>Modulus of Elasticity</u>

Values of MOE varied between 4912 MPa and 13051 MPa with a grand mean of 8437 MPa. Figure 27 displays a boxplot of MOE values. The ANOVA results indicate that significant variance exists between sites and longitudinal positions; however, no significance in radial position and interactions between factors at 95 percent confidence was observed (Table 11).

Table 2. ANOVA results for MOE (MPa).

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.920E8	7	27423206.880	14.540	.000
Intercept	7.688E9	1	7.688E9	4075.964	.000
Site	1.506E8	2	75275002.111	39.911	.000
Longitudinal	36390461.880	3	12130153.960	6.431	.001
Radial	5021982.056	2	2510991.028	1.331	.269
Error	1.886E8	100	1886083.701		
Total	8.068E9	108			
Corrected Total	3.806E8	107			

a. R Squared = .504 (Adjusted R Squared = .470)

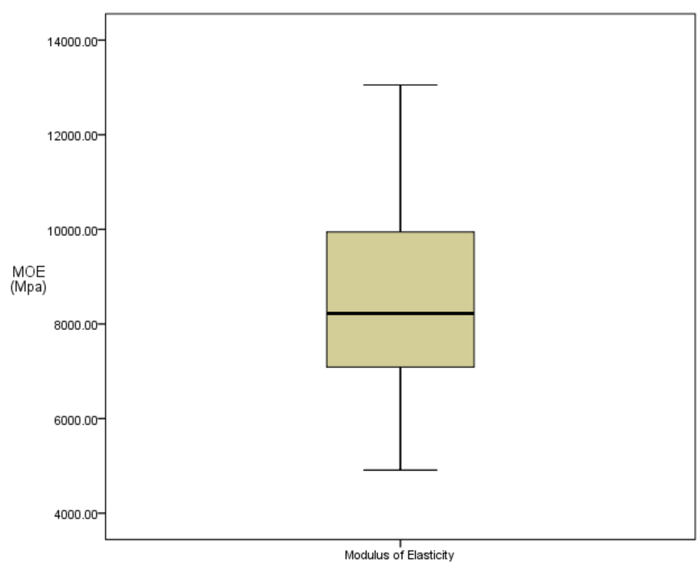

Figure 27. Boxplot of MOE (MPa) means.

The third site, the well-drained site, displayed the highest average values at 9691 MPa, with a moderate variance (Figure 28). The first site, the lowland site, had the lowest average values at 6855 MPa and the lowest variance. The second site, the upland site, displayed moderate mean values of 8736 MPa but displayed the largest variance.

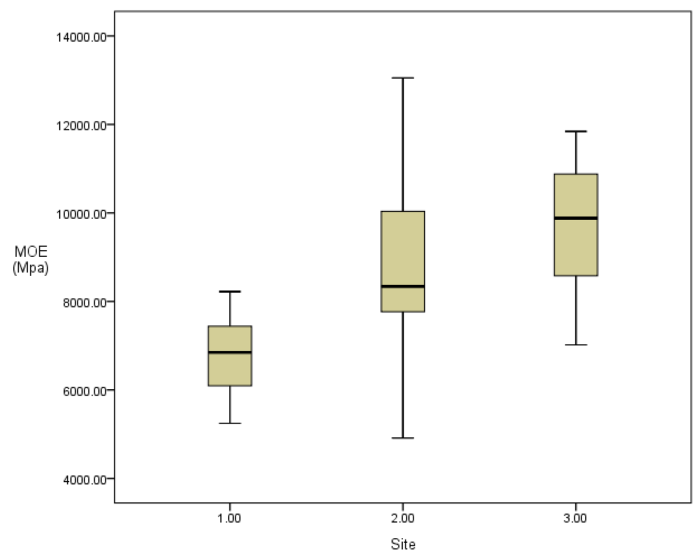

Figure 28. Boxplots of MOE (MPa) means by site.

The ANOVA results demonstrated that radial variance of MOE was not significant at 95 percent confidence. A pattern of decreasing values from pith to bark was evident on all sites, however (Figure 29).

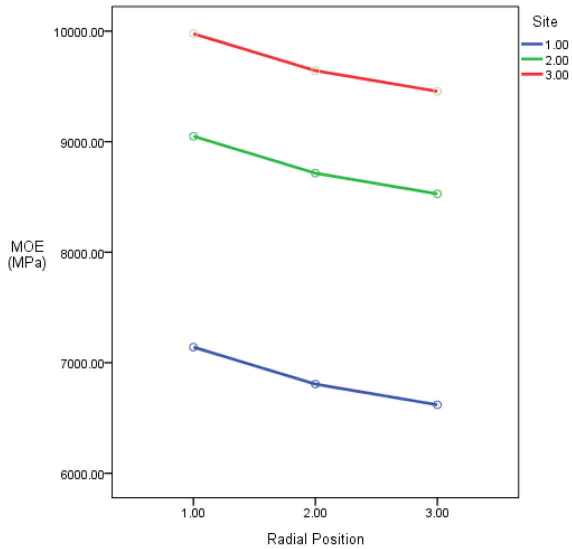

Figure 29. Radial variation of MOE (MPa) by site.

Longitudinal variation of MOE proved to be significant at 95 percent confidence and a consistent pattern of increasing MOE values form stump to crown was evident (Figure 30).

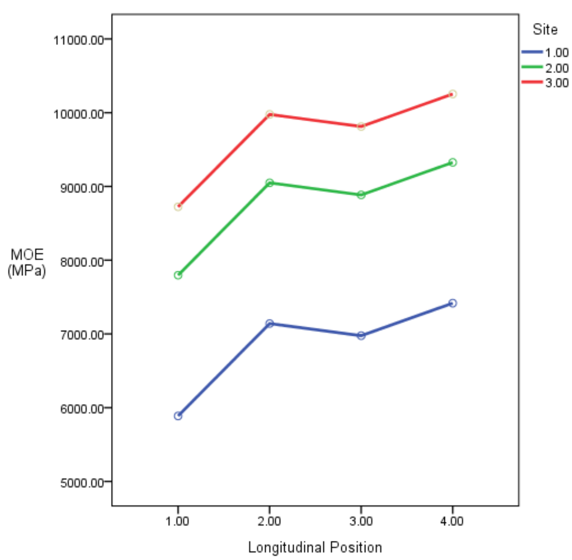

Figure 30. Longitudinal variation of MOE (MPa) by site.

The ANOVA results demonstrate that the null hypothesis of no variance in wood MOE means is rejected at 95 percent confidence. Significant variance was observed between sites and longitudinal position while variance in radial positions was not significant.

A Duncan's post hoc test was performed on the MOE mean values for sites and longitudinal positions (Figure 31). Radial positions were not significant and demonstrated no results. Duncan's test on the mean values for sites revealed each to be a distinct subset, including;

- Subset A; the first site, the lowland black ash swamp
- Subset B: the second site, the upland site.
- Subset C: the third site, the well-drained black ash site.

These results are consistent with those of relative density and density in that the mean values from the second and third site are significantly larger than those of the first. This suggests that the increased density values may be correlated to increased MOE values. However, unlike relative density and density values, MOE values were largest on the third site, the well-drained site, as opposed to site two, the upland site.

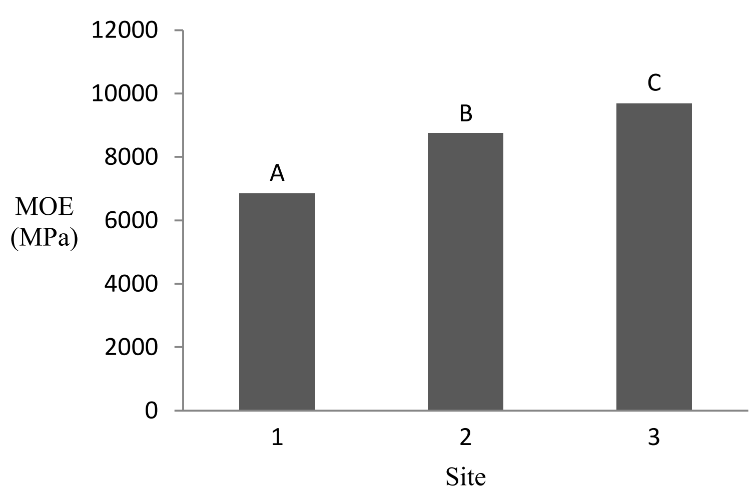

Figure 31. Post hoc test results of MOE (MPa) values by site.

Figure 32 and Figure 33 display the results of Duncan's post hoc test of MOE means, indicating two subsets of longitudinal similarity, including:

- Subset A; the first longitudinal position within the main stem, with a mean value of 7469 MPa
- Subset B; longitudinal positions two through four in the main stem, with an mean value of 8760 MPa.

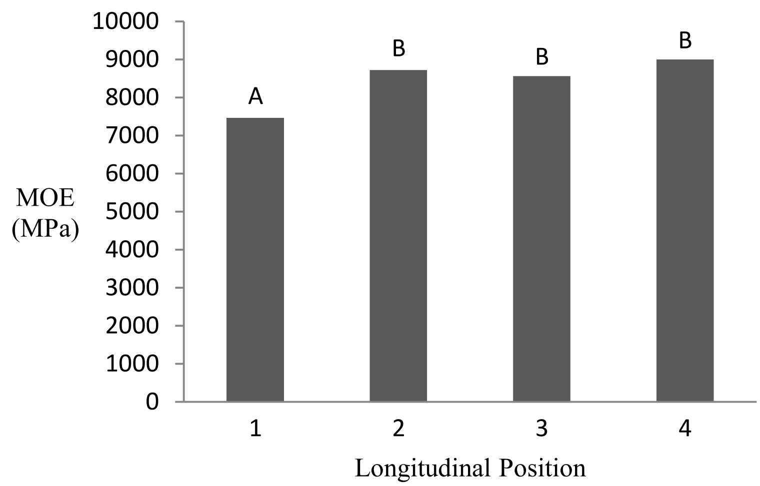

Figure 32. Post hoc test results of MOE (MPa) values by longitudinal position[1].

[1] Similar letters indicate no significant difference.

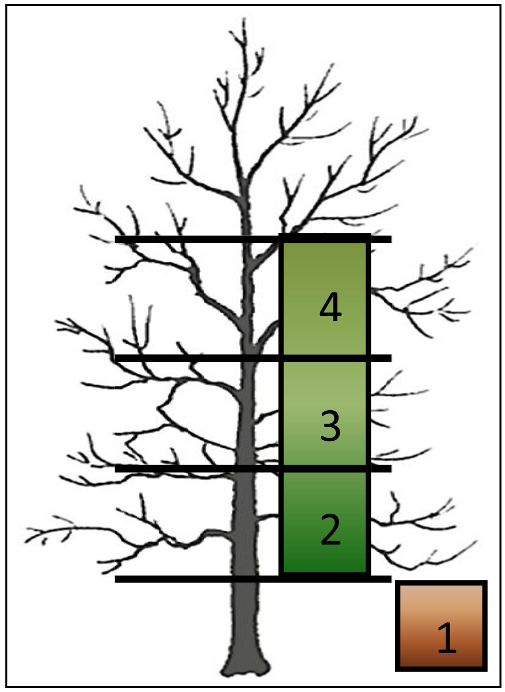

Figure 33. Post hoc test results for MOE (MPa) displaying subsets within the tree.

<u>Modulus of Rupture</u>

Values of MOR varied between 54 MPa and 120 MPa with a grand mean of 88 MPa. Figure 34 displays a boxplot of MOR values. The ANOVA results indicate that variation between sites was significant at 95 percent confidence while variations between longitudinal and radial distances and interactions between factors were not significant (Table 11).

Table 11. ANOVA results for MOR (MPa).

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	7905.769[a]	7	1129.396	10.816	.000
Intercept	842523.343	1	842523.343	8068.687	.000
Site	7758.796	2	3879.398	37.152	.000
Longitudinal	99.731	3	33.244	.318	.812
Radial	47.241	2	23.620	.226	.798
Error	10441.889	100	104.419		
Total	860871.000	108			
Corrected Total	18347.657	107			

a. R Squared = .431 (Adjusted R Squared = .391)

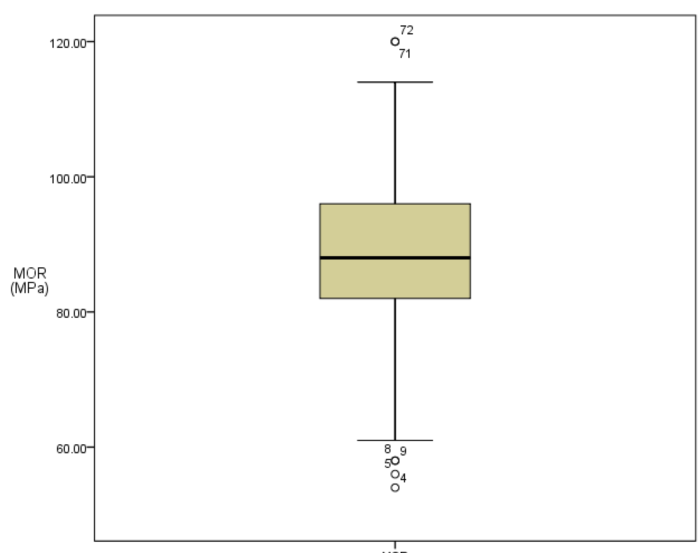

Figure 34. Boxplot of MOR (MPa) means.

The third site, the well-drained site, displayed the highest MOR values at 97 MPa (Figure 35). The second site, the upland site, displayed an average MOR of 91 MPa. Both sites demonstrated a moderate variance; however, the second site contained two outliers which cannot be explained through test error and reflect increased value within the top portion of a tree. The first site, the lowland site, displayed the lowest mean values at 77 MPa and displayed the largest variance.

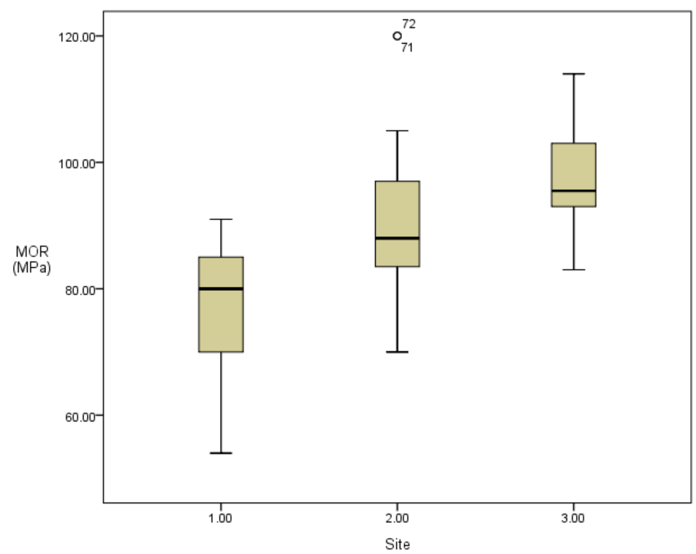

Figure 35. Boxplot comparison of MOR (MPa) values by site.

The ANOVA results demonstrated that radial and longitudinal variance of MOR was not significant at 95 percent confidence level and patterns of radial variation were negligible across all sites.

The ANOVA demonstrated that the null hypothesis of no variance in wood MOR means is rejected at 95 percent confidence. Significant variance was observed between sites while variance in radial positions and longitudinal positions was non-significant.

A Duncan’s post hoc test was performed on the MOR mean values of sites (Figure 36). Radial and longitudinal positions were not significant and demonstrated no results. Duncan’s test on the mean values for sites revealed each to be a distinct subset, including;

- Subset A; the first site, the lowland black ash swamp
- Subset B: the second site, the upland site.
- Subset C: the third site, the well-drained black ash site.

These results are consistent with those of relative density and density in that the mean values from the second and third site are significantly larger than those of the first. Further, these results are identical to those displayed for MOE and reflect the relationship between MOE and MOR, as well as the potential for increased MOR values in relation to increased density values.

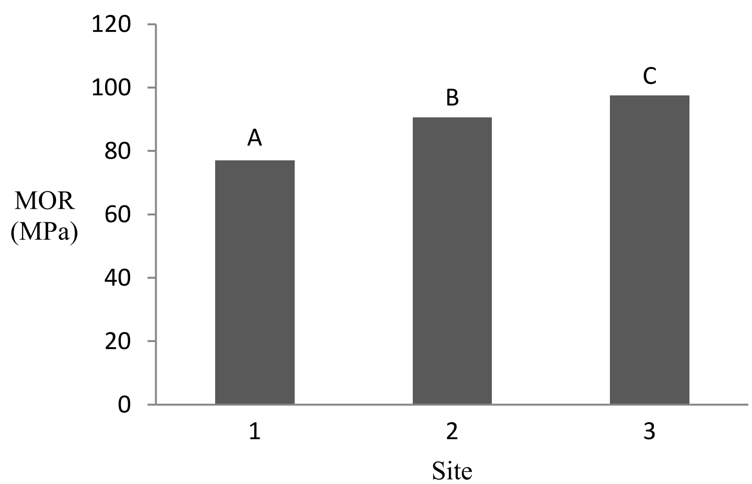

Figure 36. Post hoc test results of MOE (MPa) values by site[1].

[1] Similar letters indicate no significant difference.

Compression Parallel to the Grain

Value of compression parallel to the grain varied between 27 MPa and 62 MPa with a grand mean of 41 Mpa. Figure 37 displays a boxplot of compression parallel to the grain values. The ANOVA results indicate that significant variance exists between sites and longitudinal positions, however, no significance in radial position and interactions between factors at 95 percent confidence was observed (Table 12).

Table 12. ANOVA results for compression parallel to the grain (MPa).

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2259.346[a]	7	322.764	12.153	.000
Intercept	180164.845	1	180164.845	6783.776	.000
Site	1827.475	2	913.737	34.405	.000
Longitudinal	428.668	3	142.889	5.380	.002
Radial	3.204	2	1.602	.060	.942
Error	2655.820	100	26.558		
Total	185080.010	108			
Corrected Total	4915.165	107			

a. R^2 = .460 (Adjusted R Squared = .422)

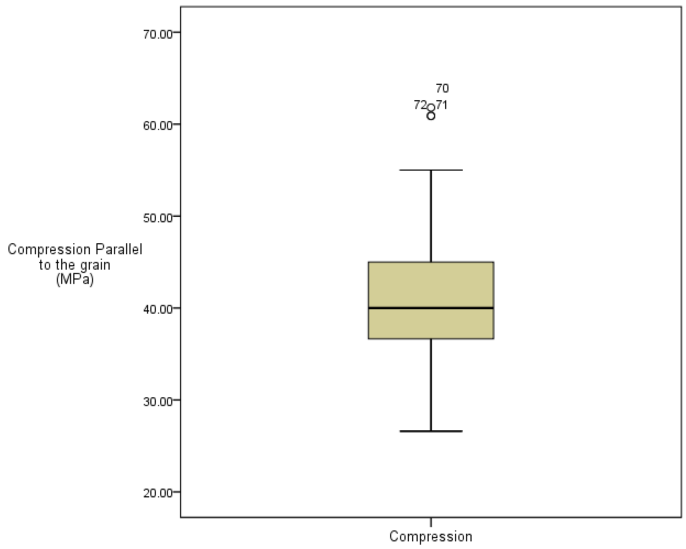

Figure 37. Boxplot of compression parallel to the grain (MPa) mean values.

The second site, the upland site, displayed the highest mean values at 46 MPa (Figure 38). The third site, the well-drained site, followed with a mean value of 39 MPa. Once again the first site, the lowland site, had the lowest mean values at 36 MPa. All three sites displayed a moderate variance, however, the second site contained three outliers, which were not a result of test error and reflect similar areas of increased properties within a tree to those found in MOR values.

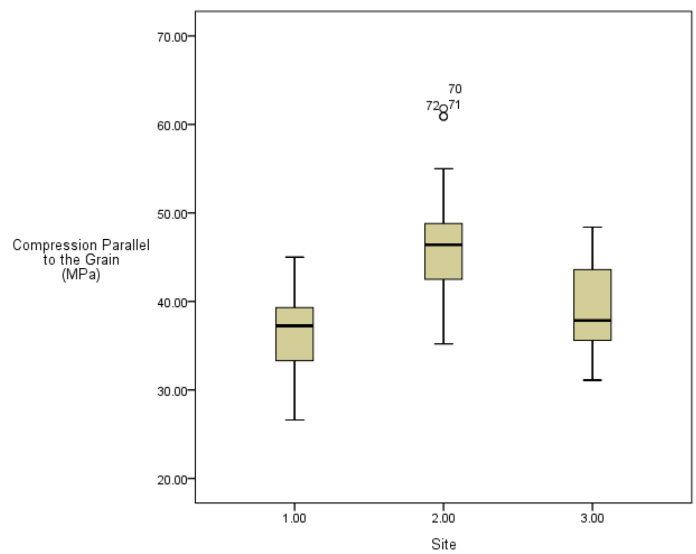

Figure 38. Boxplot comparisons of compression parallel to the grain (MPa) values by site.

The ANOVA demonstrated that radial variance of compression parallel to grain was non-significant at 95 percent confidence and patterns of radial variation were negligible across all sites. Longitudinal variation of compression parallel to the grain proved to be significant at 95 percent confidence. A consistent pattern of increasing compression values form stump to crown was evident on all sites (Figure 39).

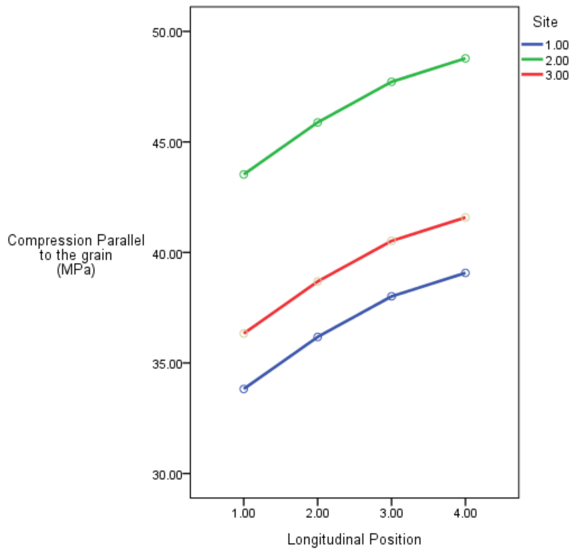

Figure 39. Longitudinal variation of compression parallel to the grain (MPa) values by site.

The ANOVA demonstrated that the null hypothesis of no variance in wood compression parallel to the grain means is rejected at 95 percent confidence. Significant variance was observed between sites and longitudinal position while variance in radial positions was not significant.

A Duncan's post hoc test was performed on the compression parallel to the grain mean values of sites and longitudinal positions. Radial positions were not significant and demonstrated no results. Duncan's test on the mean values for sites revealed each to be a distinct subset, including;

- Subset A; the first site, the lowland black ash swamp.
- Subset B: the second site, the upland site.
- Subset C: the third site, the well-drained black ash site.

These results are consistent with all previous tests in that the mean values from the second and third site are significantly larger than those of the first. However, mean values on the second site were largest as found in relative density and density values as opposed to the third site as found with MOE and MOR.

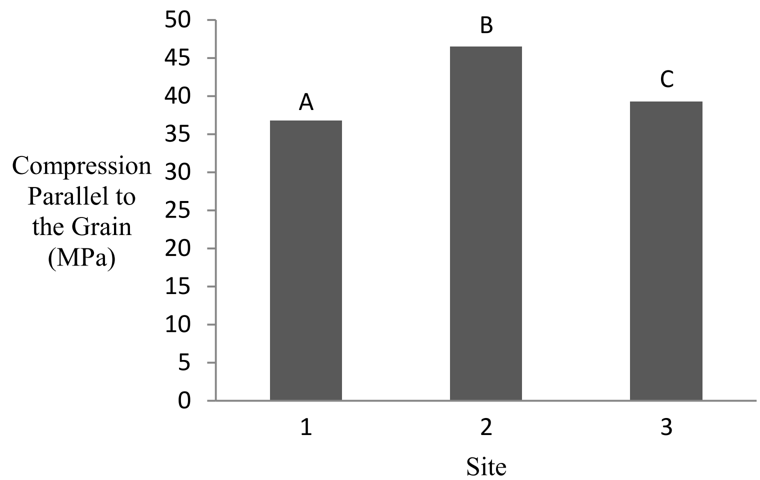

Figure 40. Post hoc test results of compression parallel to grain (MPa) values by site[1].

Figure 41 and Figure 42 display Duncan's post hoc tests of compression parallel to the grain means indicating two subsets of longitudinal similarity, including:

- Subset A; longitudinal position one and two within the main stem with a mean value of 39 MPa
- Subset B; including, longitudinal position two through four in the main stem with a mean value of 42 MPa.

[1] Similar letters indicate no significant difference.

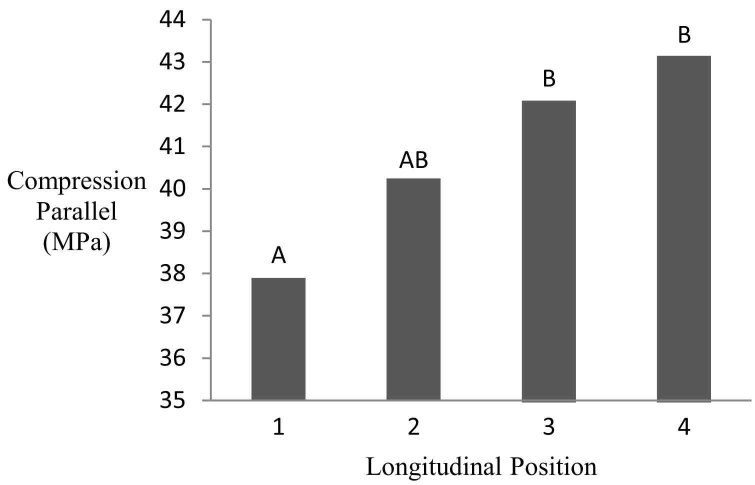

Figure 41. Post hoc test results of compression parallel to grain (MPa) values by longitudinal position[1].

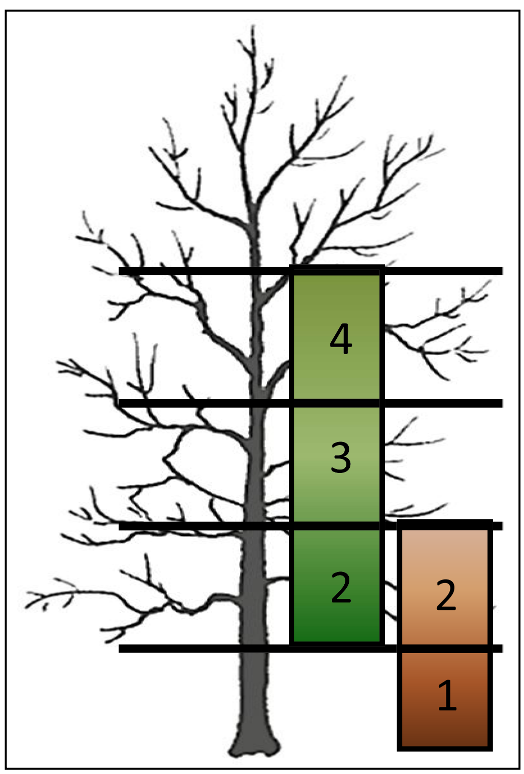

Figure 42. Post hoc test results of compression parallel to the grain displaying subsets within the tree.

[1] Similar letters indicate no significant difference.

Janka Ball Side Hardness

Values of Janka ball side hardness varied between 4699 N and 6515 N with a grand mean of 5506 N (Figure 43). The ANOVA results indicate that significant variance exists between sites and longitudinal positions; however, no significance in radial position and interactions between factors at 95 percent confidence was observed (Table 13)

Table 13. ANOVA results for Janka ball side hardness (N).

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	16223124.028[a]	7	2317589.147	3.711	.001
Intercept	3.274E9	1	3.274E9	5241.852	.000
Site	6004833.463	2	3002416.731	4.807	.010
Longitudinal	10180528.546	3	3393509.515	5.434	.002
Radial	37762.019	2	18881.009	.030	.970
Error	62455263.185	100	624552.632		
Total	3.352E9	108			
Corrected Total	78678387.213	107			

a. R Squared = .206 (Adjusted R Squared = .151)

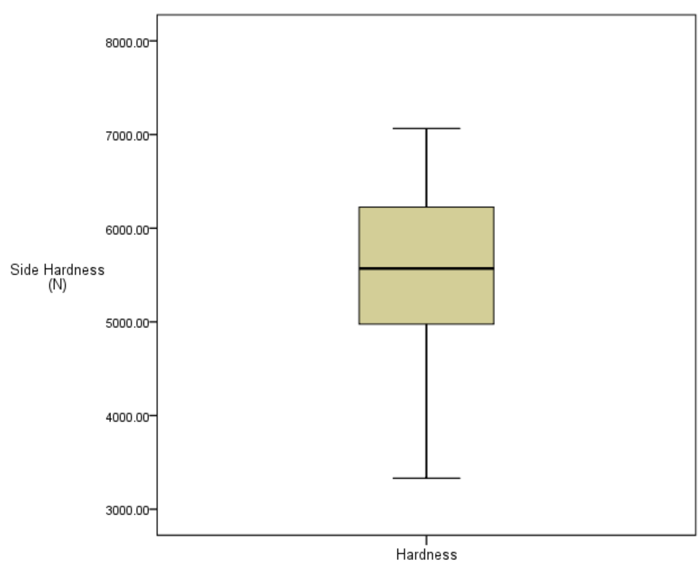

Figure 43. Boxplot of Janka Ball side hardness (N) mean values.

The third site, the well-drained site, displayed the highest mean values at 5738 N. The first site, the wetland site, displayed the lowest mean value of 5182 N. However, both sites displayed large variances. The second site, the upland site, displayed moderate mean values at 5597 N with a moderate variance (Figure 44).

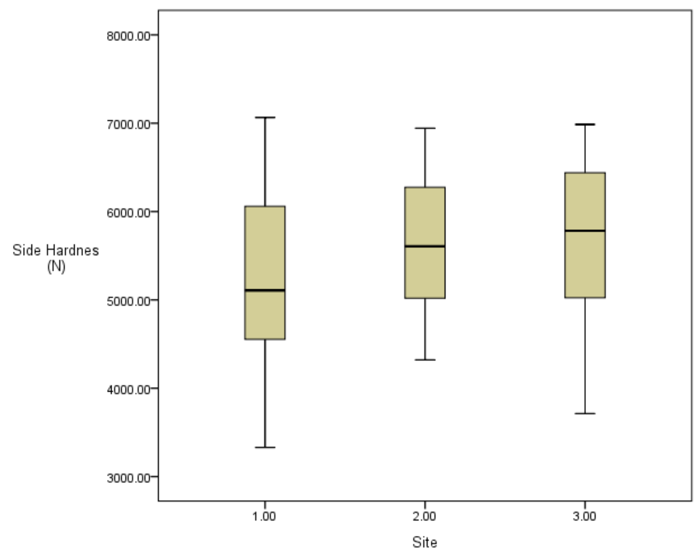

Figure 44. Boxplot comparison of Janka Ball side hardness (N) values by site.

The ANOVA demonstrated that radial variance of side hardness was non-significant at 95 percent confidence and patterns of radial variation were negligible across all sites. Longitudinal variation of side hardness proved to be significant at 95 percent confidence. A consistent pattern of decreasing side hardness values form stump to crown was evident on all sites (Figure 45).

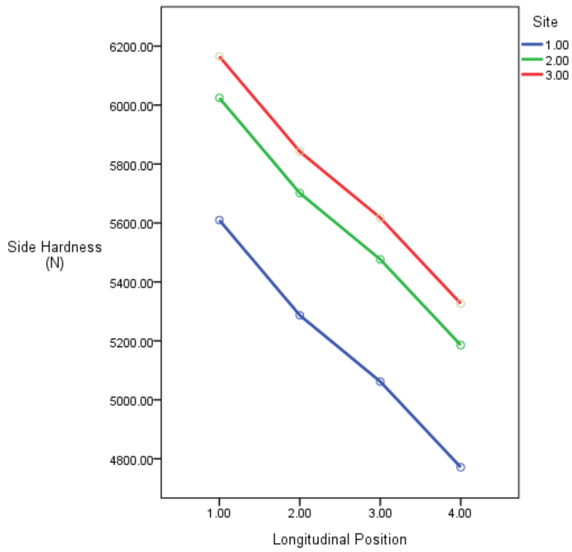

Figure 45. Longitudinal variation of Janka Ball side hardness (N) values by site.

The ANOVA demonstrated that the null hypothesis of no variance in side hardness means is rejected at 95 percent confidence. Significant variance was observed between sites and longitudinal position while variance in radial positions was not significant.

A Duncan's post hoc test was performed on the side hardness mean values of sites and longitudinal positions (Figure 46). Radial positions were not significant and demonstrated no results. The test revealed two subsets of sites:

- Subset A; the first site, consisting of the lowland black ash swamp.
- Subset B: including the second and third site, the upland and well-drained sites.

These results are consistent with all previous tests in that the mean values from the second and third site are significantly larger than those of the first. However, mean values on the third site were largest as found with MOE and MOR values as opposed to the second site as found with relative density and density.

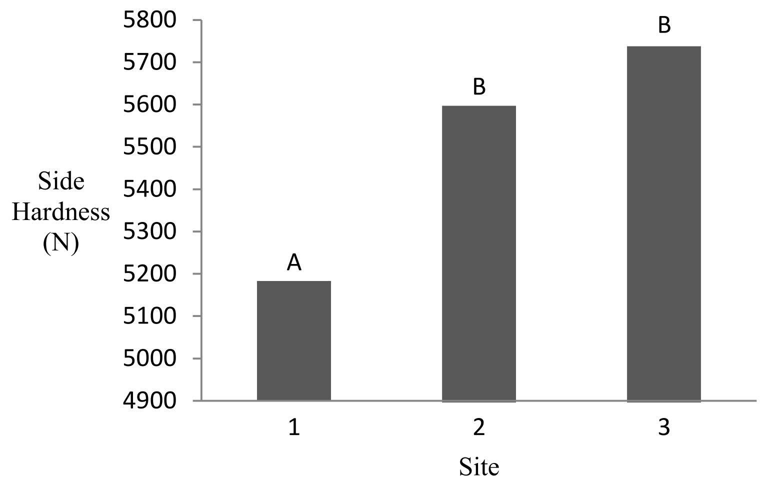

Figure 46. Post hoc test results of Janka Ball side hardness (N) values by site[1].

Figure 46 and

Figure 48 display Duncan's post hoc tests of compression parallel to the grain means indicating three subsets of longitudinal similarity, including:

- Subset A; longitudinal position one and two in the main stem with a mean value of 5240 N.
- Subset B; longitudinal position two and three in the main stem with a mean value of 5498 N
- Subset C; longitudinal positions three and four with a mean value of 5712 N.

[1] Similar letters indicate no significant difference.

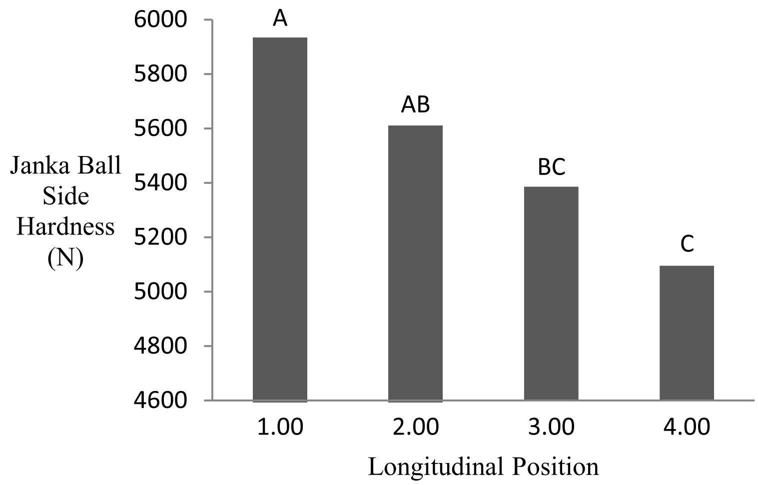

Figure 47. Post hoc test results of Janka Ball side hardness (N) values by longitudinal position.

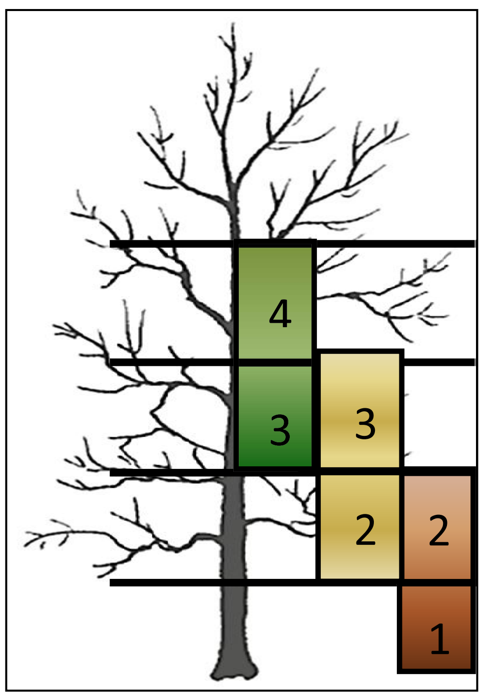

Figure 48. Post hoc test results of Janka Ball side hardness (N) displaying subsets within the tree.

Ring Density

Values of ring density varied between 367 kg/m^3 and 798 kg/m^3 with a grand mean of 623 kg/m^3. Figure 49 displays a boxplot of ring density values. The ANOVA results indicate that variation between sites was significant at 95 percent confidence level while variations between longitudinal and radial positions and interactions between factors were not significant (Table 14).

Table 14. ANOVA results of ring density (kg/m^3).

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	166637.162[a]	7	23805.309	2.796	.011
Intercept	41888294.900	1	41888294.900	4920.323	.000
Site	113262.994	2	56631.497	6.652	.002
Longitudinal	22962.733	3	7654.244	.899	.445
Radial	30411.435	2	15205.718	1.786	.173
Error	851332.175	100	8513.322		
Total	42906264.238	108			
Corrected Total	1017969.337	107			

a. R Squared = .164 (Adjusted R Squared = .105)

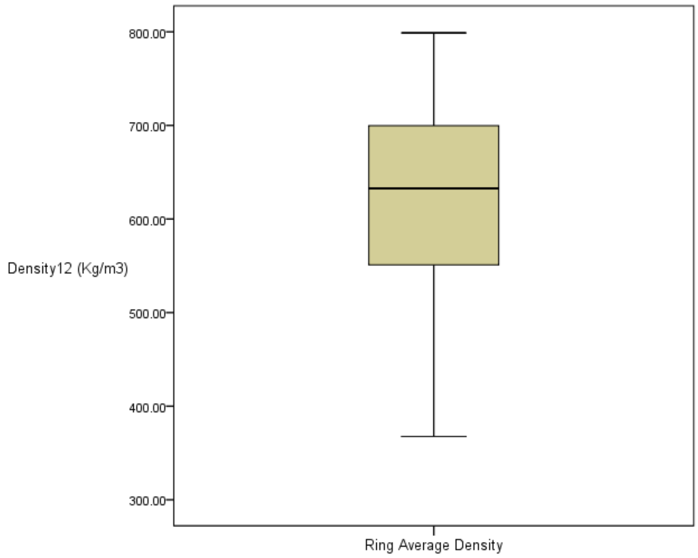

Figure 49. Boxplot of ring density means (kg/m^3).

The third site, the well-drained site, displayed the highest mean ring density values at 660 kg/m^3 (Figure 50). The second site, the upland site, displayed a mean ring density of 627 kg/m^3. Both sites demonstrated a large variance. The first site, the lowland site, displayed the lowest mean values at 581 kg/m^3 and displayed the largest variance.

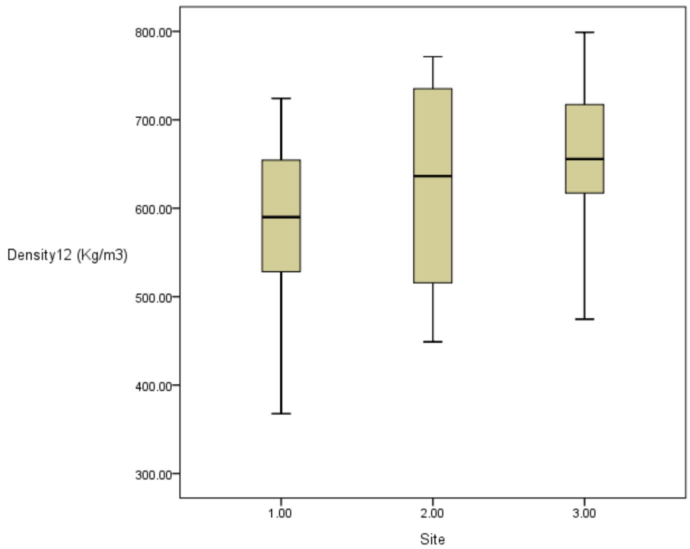

Figure 50. Boxplot of ring density (kg/m^3) means by site.

The ANOVA demonstrated that radial variance of ring density was not significant at 95 percent confidence. However, a consistent pattern of decreasing ring density from pith to bark was evident on all sites (Figure 51).

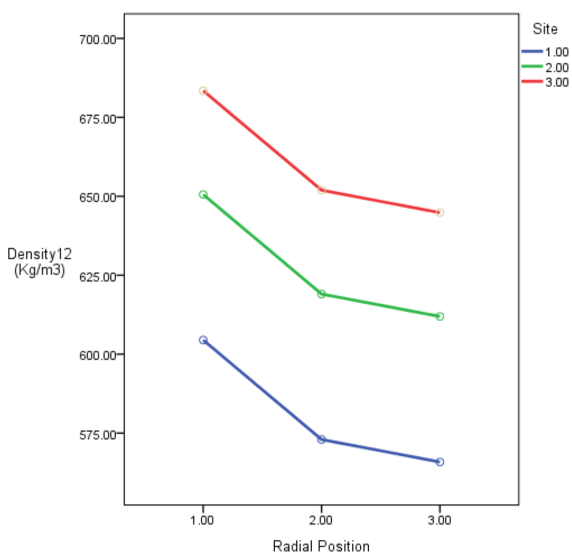

Figure 51. Radial variation of ring density (kg/m^3) by site.

Longitudinal variation of ring density proved to be non-significant at 95 percent confidence level. A pattern of increased values in the base, followed by a marginal decrease through the centre of tree and subsequently increasing towards the top was observed in all sites (Figure 52).

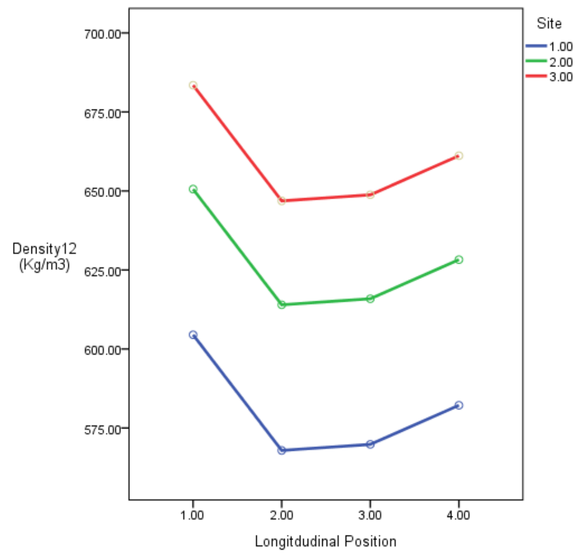

Figure 52. Longitudinal variation of ring density (kg/m^3) by site.

The ANOVA demonstrated that the null hypothesis of no variance in ring density means is rejected at 95 percent confidence. Significant variance was observed between sites, while variance in longitudinal position and radial positions was not significant.

A Duncan's post hoc test was performed on the mean ring density values for sites (Figure 53Figure 46). Radial and longitudinal positions were not significant and demonstrated no results. The test revealed two subsets of sites:

- Subset A; the first site, consisting of the lowland black ash swamp.

- Subset B: including the second and third site, the upland site and well-drained site with a mean value 643 kg/m^3.

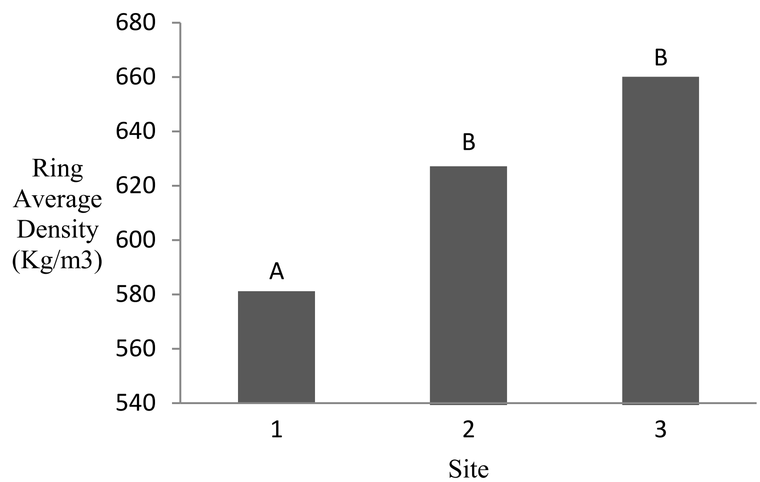

Figure 53. Post hoc test results of ring density (kg/m^3) by site[1].

[1] Similar letters indicate no significant difference.

Ring Width

Values of ring width varied between 0.39 mm and 2.39 mm with a grand mean of 1.39 mm. Figure 54 displays a boxplot of ring width values. The ANOVA results indicate that significant variance exists between sites and longitudinal positions; however, no significance in radial position and interactions between factors at 95 percent confidence was observed (Table 15).

Table 15. ANOVA results for ring width (mm).

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	8.609[a]	7	1.230	15.487	.000
Intercept	208.639	1	208.639	2627.350	.000
Site	6.404	2	3.202	40.321	.000
Longitudinal	1.872	3	.624	7.856	.000
Radial	.334	2	.167	2.101	.128
Error	7.941	100	.079		
Total	225.189	108			
Corrected Total	16.550	107			

a. R Squared = .520 (Adjusted R Squared = .487)

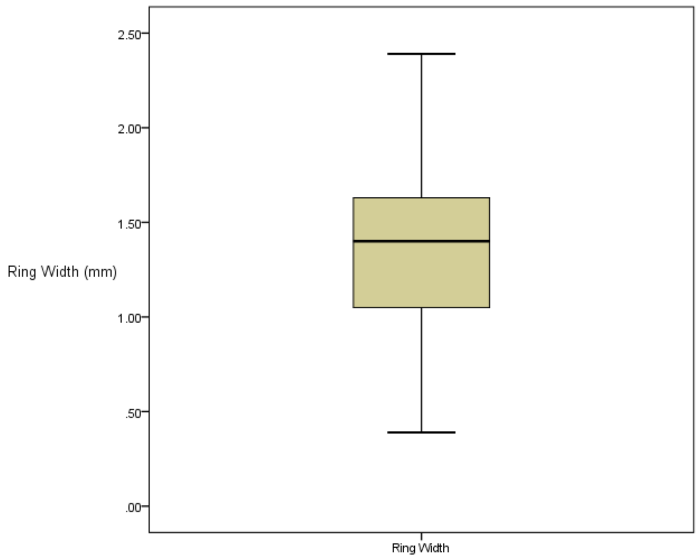

Figure 54. Boxplot of ring width (mm) means.

The third site, the well-drained site, displayed the highest average values at 1.63 mm, with a moderate variance (Figure 55). The first site, the lowland site, had the lowest average values at 1.05 mm and the lowest variance. The second site, the upland site, displayed moderate mean values of 1.48 mm but displayed the largest variance. All sites contained outlier values, which are attributed to the limited sample size at each height in the tree.

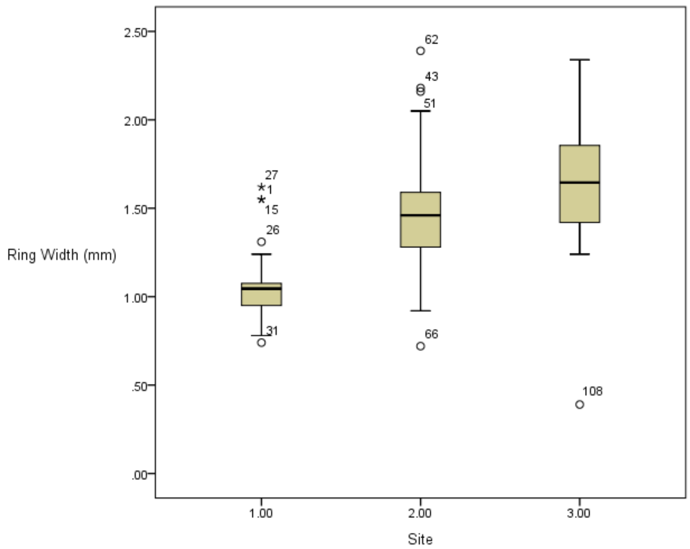

Figure 55. Boxplot of ring width (mm) means by site.

The ANOVA demonstrated that radial variance of ring width was not significant at 95 percent confidence and patterns of radial variation were negligible across all sites. Longitudinal variation of ring width proved to be significant at 95 percent confidence. Large ring widths in longitudinal position one were followed by a decline to a constant level in the remaining positions (Figure 56).

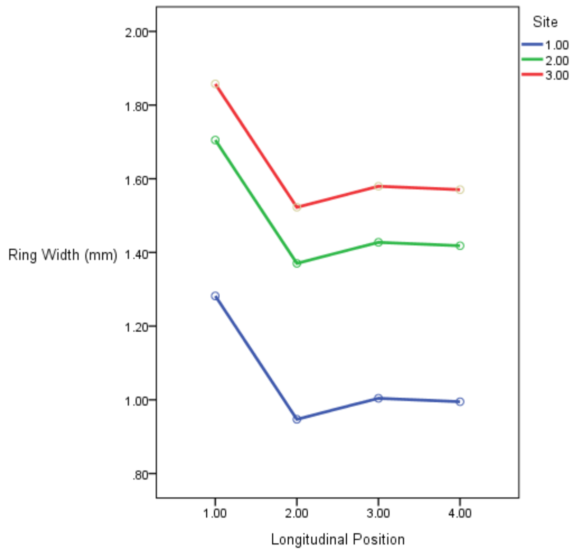

Figure 56. Longitudinal variation of ring width (mm) by site.

The ANOVA demonstrated that the null hypothesis of no variance in ring density means is rejected at 95 percent confidence. Significant variance was observed between sites and longitudinal position while variance in radial positions was not significant.

A Duncan's post hoc test was performed on the ring width mean values of sites and longitudinal positions. Radial positions were not significant and demonstrated no results. Duncan's test on the mean values for sites revealed each to be a distinct subset, including;

- Subset A; the first site, the lowland black ash swamp.
- Subset B: the second site, the upland site.
- Subset C: the third site, the well-drained site.

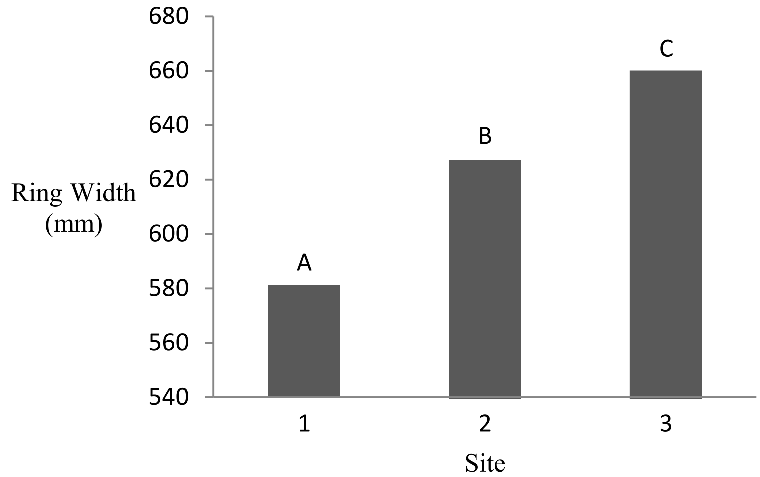

Figure 57. Post hoc test results for ring width (mm) by site[1].

Figure 59 displays Duncan's post hoc test of mean ring width values indicating two subsets of longitudinal similarity, including:

- Subset A; longitudinal position one within the main stem with a mean value of 1.61 mm.
- Subset B; including, longitudinal position two through four in the main stem with a mean value of 1.32 mm.

[1] Similar letters indicate no significant difference.

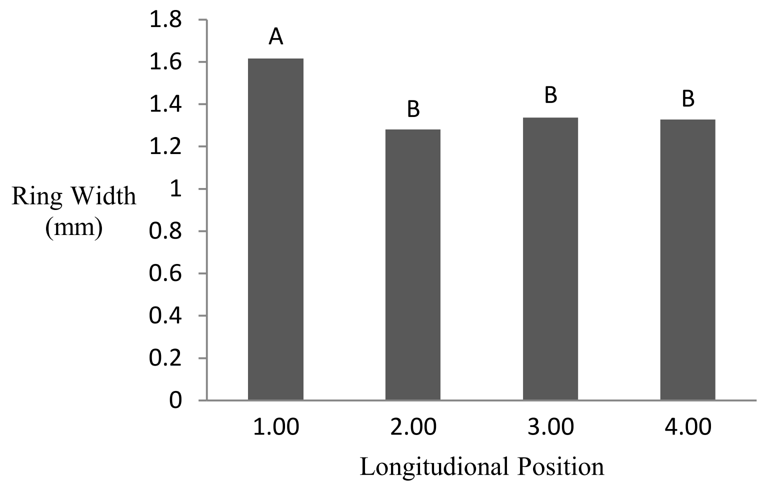

Figure 58. Post hoc test results for ring width (mm) by longitudinal position[1].

[1] Similar letters indicate no significant difference.

Percentage of Latewood

The percentage of latewood within each ring varied between 28 percent and 94 percent with a grand mean of 57 percent. Figure 59 displays boxplots of percentage of latewood values. The ANOVA results indicate that significant variance exists between sites, radial and longitudinal positions at 95 percent confidence (Table 16).

Table 16. ANOVA results of latewood percentage (%).

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	11010.279[a]	7	1572.897	12.657	.000
Intercept	353639.056	1	353639.056	2845.604	.000
Site	7533.840	2	3766.920	30.311	.000
Longitudinal	1008.057	3	336.019	2.704	.049
Radial	2468.382	2	1234.191	9.931	.000
Error	12427.557	100	124.276		
Total	377076.891	108			
Corrected Total	23437.836	107			

a. R Squared = .470 (Adjusted R Squared = .433)

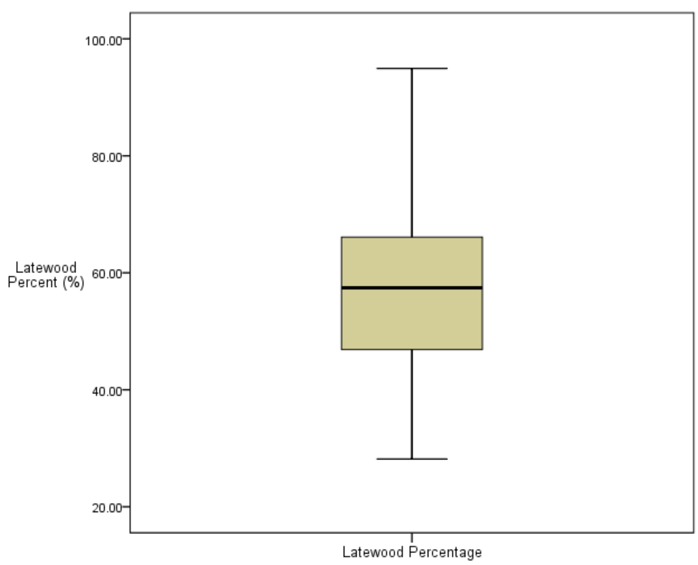

Figure 59. Boxplot of mean percentage of latewood (%).

The third site, the well-drained site, displayed the highest proportion of latewood within each ring at 64 percent, with a moderate variance (Figure 60). The first site, the lowland site, had the lowest proportion of latewood at 45 percent and the lowest variance. The second site, the upland site, displayed moderate proportions of latewood at 61 percent but displayed the largest variance.

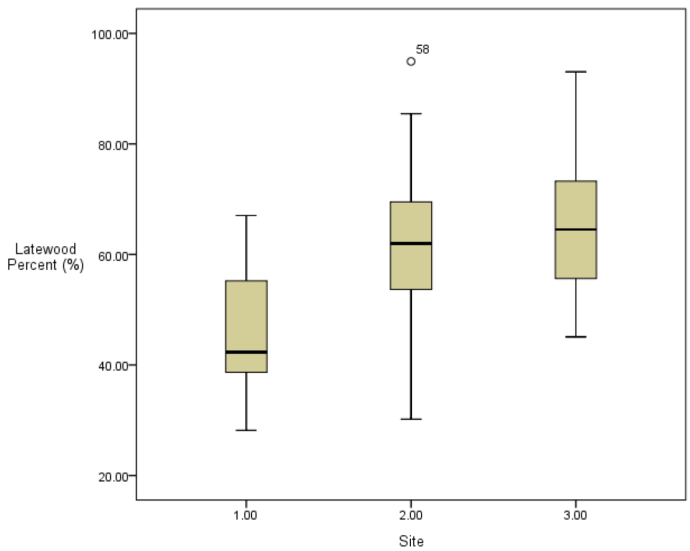

Figure 60. Boxplot plots of latewood percentage (%) by site.

The ANOVA demonstrated that radial variance of MOE was significant at 95 percent confidence. A consistent pattern of decreasing proportion of latewood from pith to bark was evident on all sites (Figure 61).

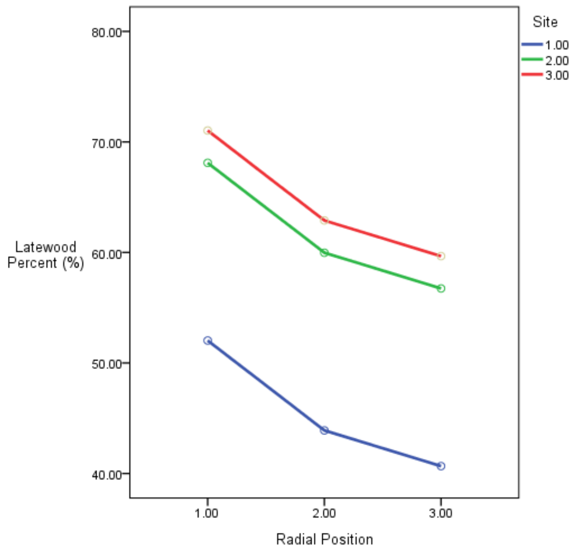

Figure 61. Radial variation of latewood percentage (%) by site.

Longitudinal variation of latewood percent proved to be significant at 95 percent confidence and a consistent pattern of increased values in the base, followed by a marginal decrease through the centre of tree and increasing towards the top was observed (Figure 62).

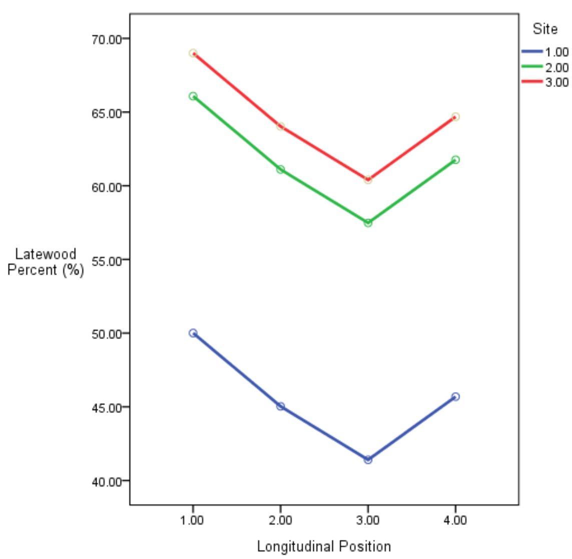

Figure 62. Longitudinal variation of latewood percentage (%) by site.

The ANOVA demonstrates that the null hypothesis of no variance in mean values of latewood percent is rejected at 95 percent confidence. Significant variance was observed between sites as well as radial and longitudinal positions.

A Duncan's post hoc test was performed on the values of latewood percent for sites (Figure 63). The test revealed two subsets of sites:

- Subset A; the first site, consisting of the lowland black ash swamp.
- Subset B: including the second and third site, the upland site and well-drained site.

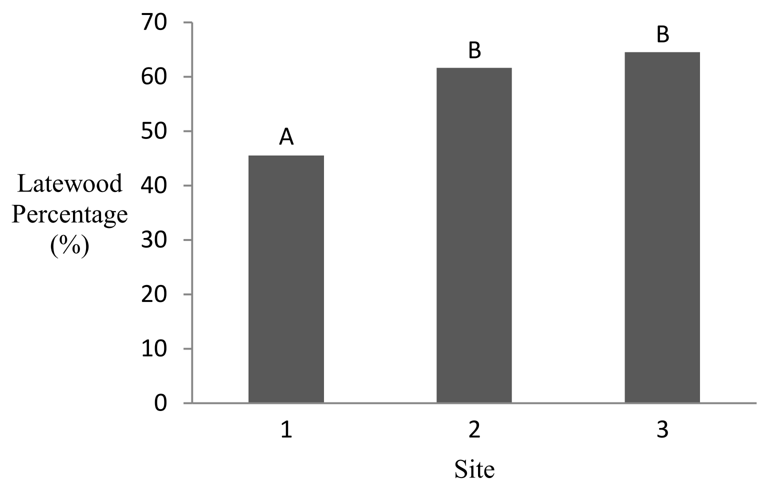

Figure 63. Post hoc test results for latewood percent (%) by site[1].

Figure 64 display the results of Duncan's post hoc test of latewood percent by radial position, indicating two subsets of radial similarity, including:

[1] Similar letters indicate no significant difference.

- Subset A; the first radial position, with an average value of 64 percent.

- Subset B; radial positions two and three, with an average value of 54 percent.

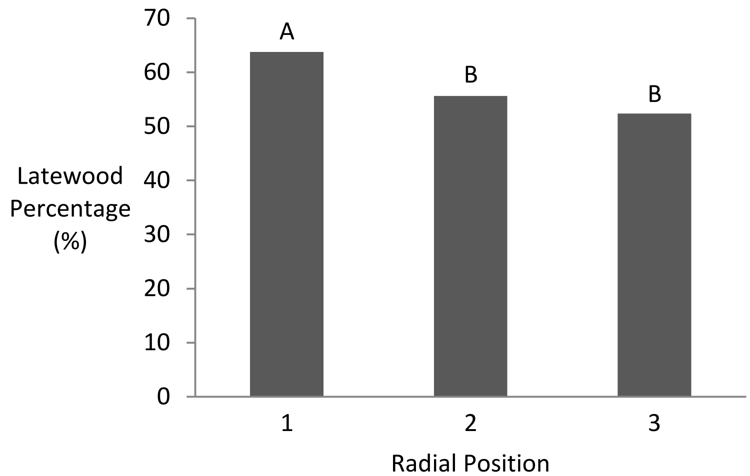

Figure 64. Post hoc test results for latewood percentage (%) by radial positions[1].

Figure 65 displays the results of Duncan's post hoc test for mean latewood percent, indicating two subsets of longitudinal similarity, including:

- Subset A; longitudinal positions two, three and four within the main stem, with an average value of 56 percent.

- Subset B; longitudinal positions one, two and four in the main stem, with an average value of 59 percent.

[1] Similar letters indicate no significant difference.

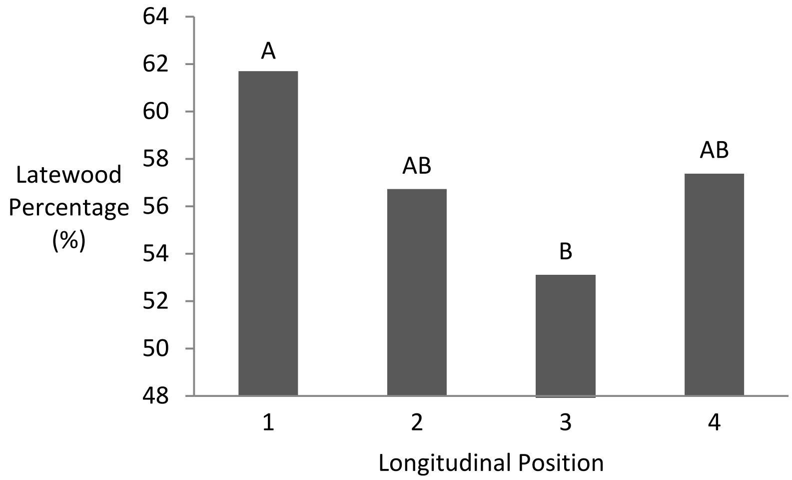

Figure 65. Post hoc test results of latewood percent (%) by longitudinal position[1].

[1] Similar letters indicate no significant difference.

VARIANCE IN JUVENILE CORE PROPERTIES

Juvenile Core MOE

Values of juvenile core MOE varied between 5054 MPa and 11 899 MPa with a grand mean of 8722 MPa. Figure 66 displays boxplots of juvenile core MOE values. The ANOVA results indicate that significant variance exists between sites; however, no significance in longitudinal position and interactions between factors at 95 percent confidence was observed (Table 17).

Table 17. ANOVA of juvenile core MOE (MPa).

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	74419440.389[a]	5	14883888.078	7.466	.000
Intercept	2.739E9	1	2.739E9	1373.726	.000
Site	61155637.167	2	30577818.583	15.338	.000
Longitudinal	13263803.222	3	4421267.741	2.218	.107
Error	59809814.611	30	1993660.487		
Total	2.873E9	36			
Corrected Total	1.342E8	35			

R Squared = .554 (Adjusted R Squared = .480)

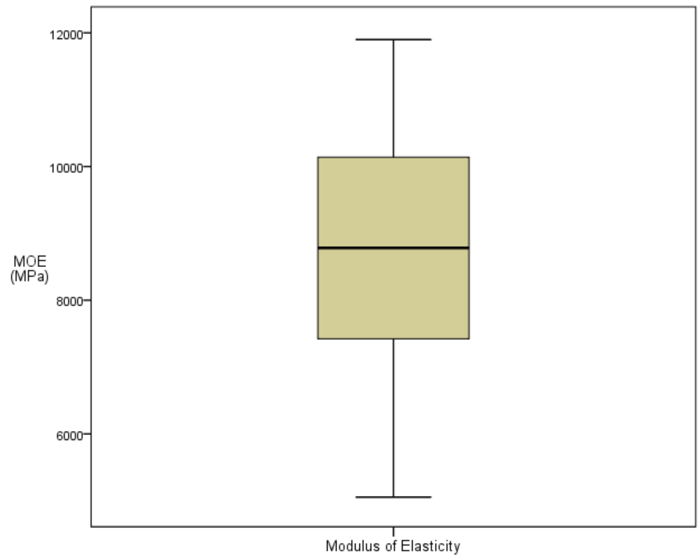

Figure 66. Boxplot of juvenile core MOE (MPa) values.

As with whole tree MOE values, the third site, displayed the highest average values at 9949 MPa, with a moderate variance (Figure 67). The first site, the lowland site, had the lowest average values at 6917 MPa and the lowest variance. The second site, the upland site, displayed moderate mean values of 9300 MPa but displayed the largest variance.

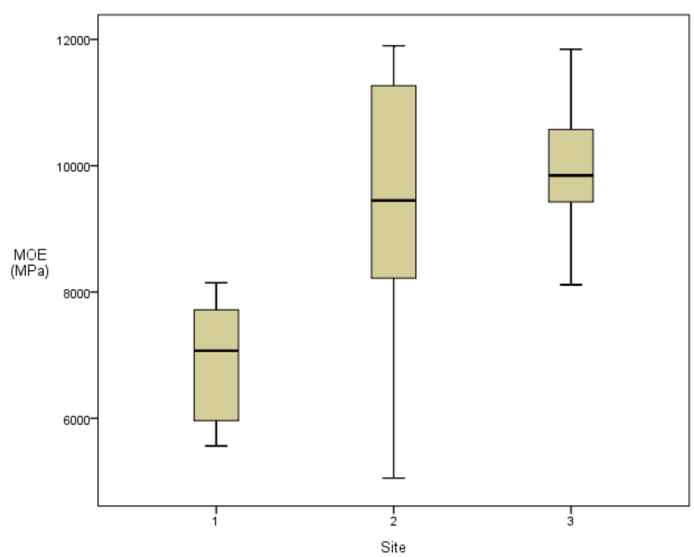

Figure 67. Boxplot of juvenile core MOE (MPa) values by site.

Longitudinal variation of MOE proved to be non-significant at 95 percent confidence, however, a consistent pattern of increasing MOE values from stump to crown was evident on all sites (Figure 68). This pattern matched closely to that found in whole tree MOE values.

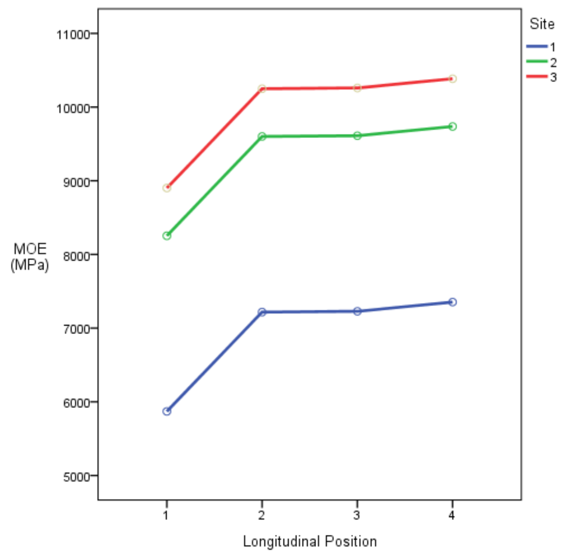

Figure 68. Longitudinal variation of juvenile core MOE (MPa) values.

The ANOVA demonstrates that the null hypothesis of no variance in juvenile core MOE values is rejected at 95 percent confidence. Significant variance was observed between sites, while variance in longitudinal positions was not significant.

A Duncan's post hoc test was performed on the MOE mean values for sites (Figure 69). Unlike whole tree MOE values, Duncan's test on the juvenile core values for sites revealed two subsets, including;

- Subset A; the first site, the lowland black ash swamp.
- Subset B: including the second and third site, the upland site and well-drained site, respectively.

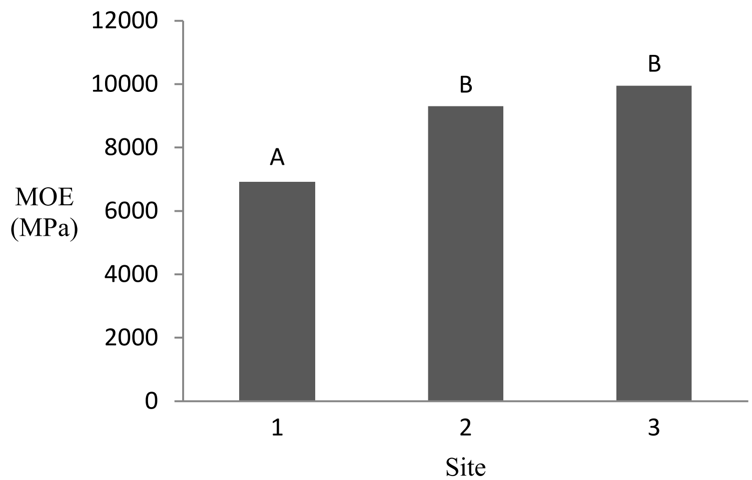

Figure 69. Post hoc test results of juvenile core MOE (MPa) by site[1].

[1] Similar letters indicate no significant difference.

Juvenile Core Compression Parallel to the Grain

Values of compression parallel to the grain varied between 27 MPa and 62 MPa with a grand mean of 41Mpa. Figure 70 displays a boxplot of values. The ANOVA results indicate that significant variation exists between sites, however, no significance in longitudinal position and interactions between factors at 95 percent confidence was observed (Table 18).

Table 18. ANOVA results of juvenile core compression parallel to the grain values.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	778.804[a]	5	155.761	5.427	.001
Intercept	60425.834	1	60425.834	2105.398	.000
Site	657.407	2	328.704	11.453	.000
Longitudinal	121.396	3	40.465	1.410	.259
Error	861.013	30	28.700		
Total	62065.650	36			
Corrected Total	1639.816	35			

a. R Squared = .475 (Adjusted R Squared = .387)

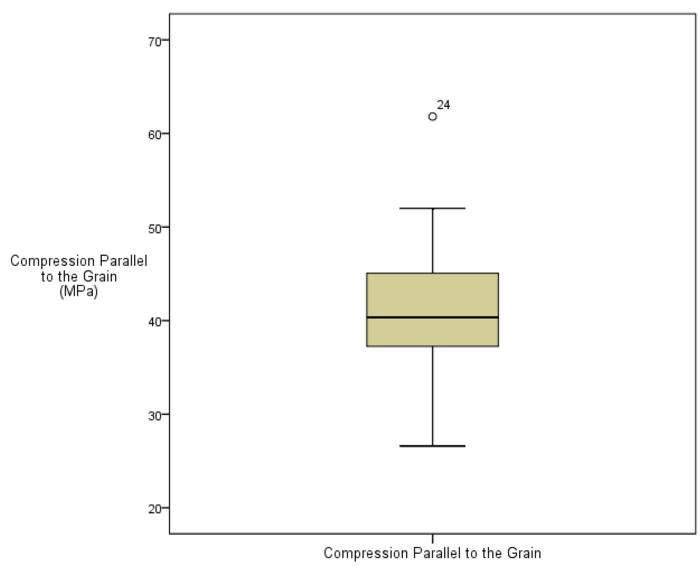

Figure 70. Boxplot of juvenile core compression parallel to the grain (MPa) means values.

As with whole tree values, the second site, the upland site, displayed the highest mean values at 47 MPa (Figure 71). The third site, the well-drained site, followed with a mean value of 39 MPa. Once again the first site, the lowland site, had the lowest mean values at 37 MPa. All three sites displayed a moderate variance.

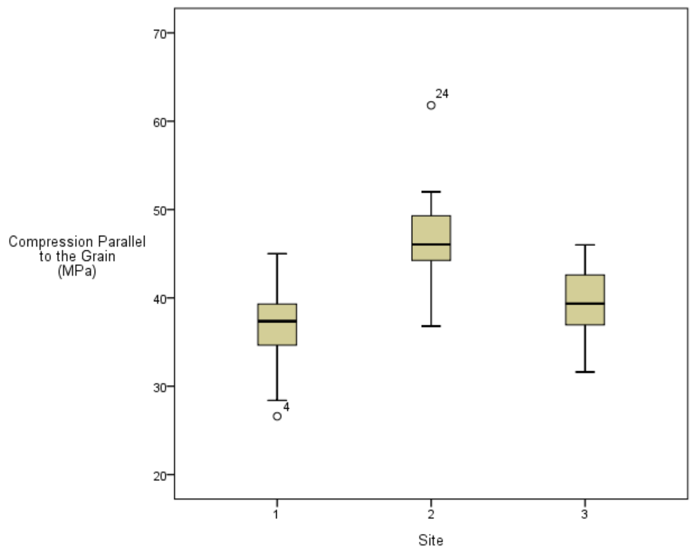

Figure 71. Boxplots of juvenile core compression parallel to the grain (MPa) by site.

The ANOVA demonstrated that the null hypothesis of no variance in wood compression parallel to the grain means is rejected at 95 percent confidence. Significant variance was observed between sites while variance in longitudinal position was not significant and patterns were negligible.

A Duncan's post hoc test was performed on the compression parallel to the grain mean values of sites (Figure 72). Longitudinal positions were not significant and demonstrated no results. Unlike whole tree values, Duncan's test on the mean values for sites revealed two subsets of sites, including;

- Subset A; the first and third site, the lowland swamp and the well-drained site.

- Subset B: the second site, the upland site.

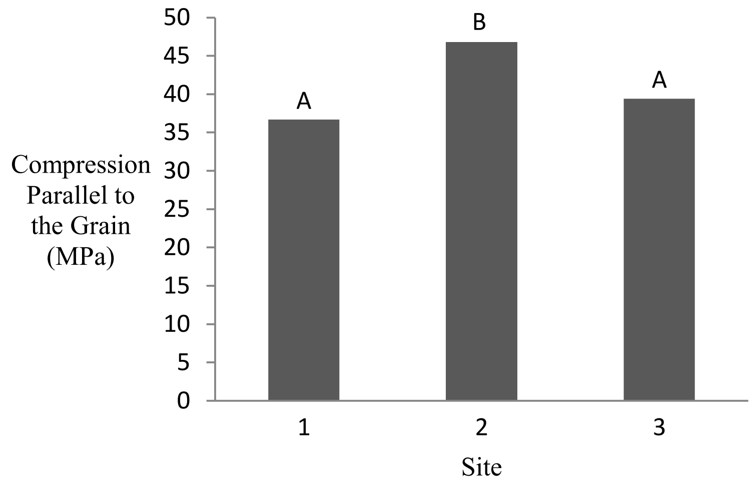

Figure 72. Post hoc test results of juvenile core compression parallel to the grain (MPa) by site[1].

[1] Similar letters indicate no significant difference.

Juvenile Core Side Hardness

Values of juvenile core Janka ball side hardness values varied between 3330 N and 7625 N with a grand mean of 5547 N. Figure 73 displays a boxplot of juvenile core side harness values. The ANOVA results indicate that no significant variance exists between sites, longitudinal position or interactions between factors at 95 percent confidence (Table 19).

Table 19. ANOVA results for juvenile core Janka ball side hardness (N).

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	8223993.611[a]	5	1644798.722	1.941	.117
Intercept	1.108E9	1	1.108E9	1307.127	.000
Site	4349691.722	2	2174845.861	2.566	.094
Longitudinal	3874301.889	3	1291433.963	1.524	.229
Error	25426306.944	30	847543.565		
Total	1.141E9	36			
Corrected Total	33650300.556	35			

a. R Squared = .244 (Adjusted R Squared = .118)

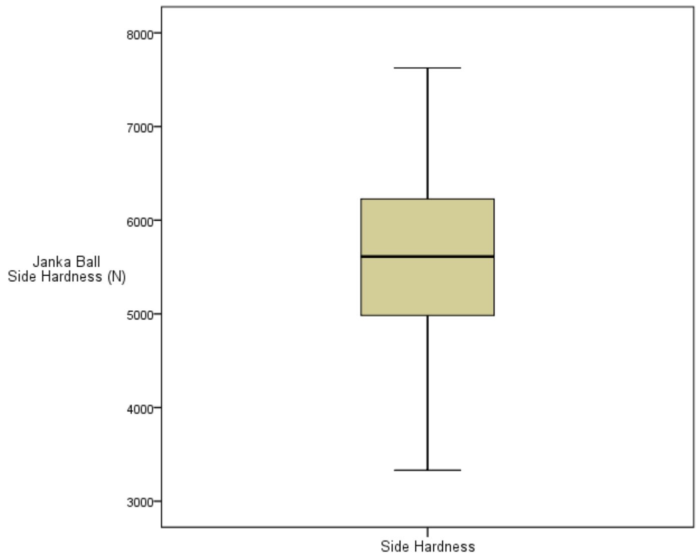

Figure 73. Boxplot of juvenile core Janka Ball side hardness (N).

Unlike whole tree values, the second site, the upland site, displayed the highest mean values at 5968 N with a small variance. The first site, the wetland site, displayed the lowest mean value of 5116 N. The third site, the upland site, displayed moderate mean values at 5597 N. However, both sites displayed large variances (Figure 74).

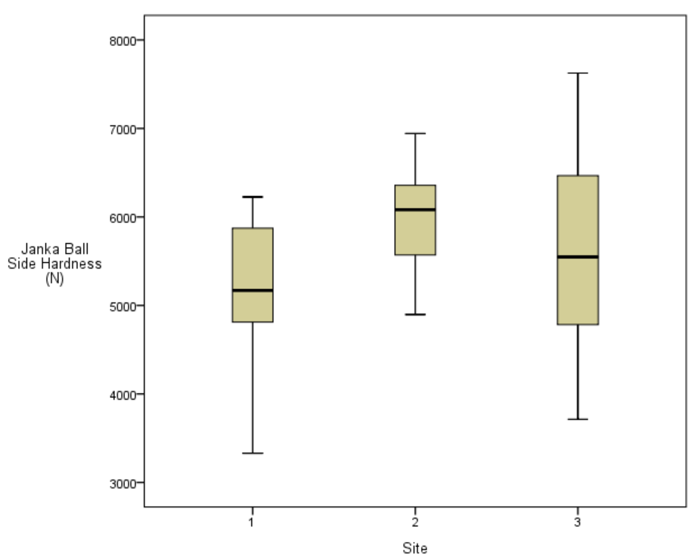

Figure 74. Boxplot comparison of juvenile core Janka Ball side hardness (N) values.

Longitudinal variation of side hardness proved to be non-significant at 95 percent confidence. However, a consistent pattern of decreasing side hardness values form stump to crown was evident on all sites (**Error! Reference source not found.**).

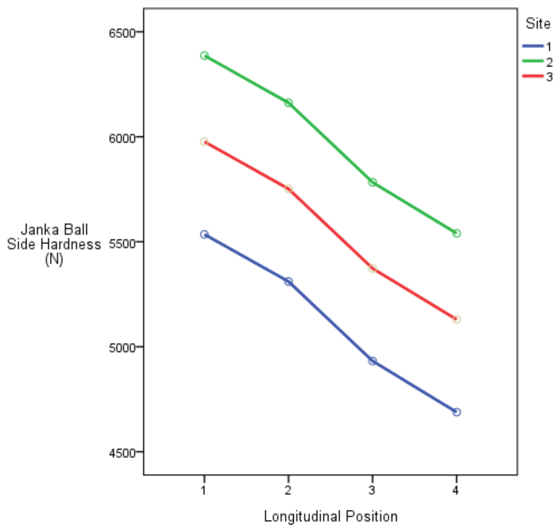

Figure 75. Longitudinal variation of juvenile core Janka ball side hardness (N) values.

The ANOVA demonstrated that the null hypothesis of no variance in side hardness means fails to be rejected at 95 percent confidence. Significant variance was not observed between sites or longitudinal position. A Duncan's post hoc test was not performed on the side hardness mean values of sites or longitudinal positions.

RELATIVE DENSITY AND MECHANICAL PROPERTY RELATIONSHIP

Linear, Logarithmic and Exponential Equations

Linear, logarithmic and exponential equation coefficients and coefficients of determination for relative density$_{12}$ as a function of measured properties; MOE, MOR, compression parallel to the grain and side hardness, are presented in Table 20. Relationships are plotted in Appendix IV to VI and demonstrate a positive correlation between relative$_{12}$ density and measured properties. All regression methods display a significant relationship between the variables at 95 percent confidence. Consequently, the null hypothesis, that the slope equals zero is rejected for all models.

Table 20. Linear, logarithmic and exponential equation coefficients and coefficients of determination for relative density$_{12}$ as a function of measured properties.

		Model Summary					Parameter Estimates	
	Equation	R^2	F	df1	df2	Sig.	Constant	b1
MOE	Linear	.387	67.007	1	106	.000	-7128.310	26.968
	Logarithmic	.381	65.254	1	106	.000	-89107.273	15348.494
	Exponential	.378	64.384	1	106	.000	1277.981	.003
MOR	Linear	.436	81.982	1	106	.000	-26.360	.199
	Logarithmic	.437	82.200	1	106	.000	-636.807	114.099
	Exponential	.436	81.837	1	106	.000	22.194	.002
Compression parallel to the grain	Linear	.489	101.360	1	106	.000	-21.998	.109
	Logarithmic	.485	99.827	1	106	.000	-354.652	62.231
	Exponential	.507	108.808	1	106	.000	8.643	.003
Side Hardness	Linear	.453	87.650	1	106	.000	-2145.031	13.256
	Logarithmic	.463	91.515	1	106	.000	-43401.688	7695.540
	Exponential	.446	85.175	1	106	.000	1273.185	.003

Comparison with Published Equations

The FPL has developed exponential equations aimed at predicting mechanical properties in hardwoods and softwoods throughout the United States. Utilizing collected data from the present study, a comparison between the FPL hardwood model and the linear equations identified in Table 8 was conducted. The mean, standard error, and upper and lower bound values of each model are presented Table 21.

Table 21. Descriptive statistics of actual and predicted values of measured properties.

Measured Property	Model	Mean	Standard Error	Lower Bound	Upper Bound
MOE (MPa)	Measured Property Values	8437	181.474	4912	13051
	Predicted Values - Linear Model	8437	112.938	6248	11102
	USDA Hardwood Model	11223	57.168	10097	12550
MOR (MPa)	Measured Property Values	88	1.260	54	120
	Predicted Values - Linear Model	88	0.832	72	108
	USDA Hardwood Model	92	0.755	78	110
Compression (MPa)	Measured Property Values	41	0.652	27	62
	Predicted Values - Linear Model	41	0.456	32	52
	USDA Hardwood Model	47	0.301	41	54
Side Hardness (N)	Measured Property Values	5506	82.513	3330	7065
	Predicted Values - Linear Model	5506	55.513	4430	6816
	USDA Hardwood Model	4882	73.691	3531	6759

The results indicate that the linear model from the Thunder Bay seed zone produced the most accurate results when compared to actual values. The FPL hardwood model produced values 25 percent larger for MOE, 4 percent larger for MOR, 12 percent larger for compression parallel to the grain and 12 percent lower for side hardness.

DISCUSSION

This study was designed to evaluate the change in mechanical properties at varying longitudinal and radial positions within mature black ash stems grown in the Thunder Bay seed zone. The study was based on the evaluation of small clear specimens of wood in a number of properties, including; relative density, density, MOE, MOR, compression parallel to the grain, Janka Ball side hardness and X-ray densitometry. It is well understood that changes in wood properties occur based on the direction of measure; however, this change is not well understood in many species. It was hypothesized that differing longitudinal and radial positions would result in distinct variations in mechanical properties. It was also assumed that differing site characteristics would result in variations in mechanical properties.

LONGITUDINAL AND RADIAL VARIANCE IN WHOLE TREE PROPERTIES

Relative Density, Density and Ring Density

Relative density$_{OD}$ mean values were higher than relative density$_{12}$, while density$_{12}$ had the highest values. This trend is consistent with stated principles in wood science indicating that increased moisture content results in higher density values and lower relative density values (Bowyer *et al.,* 2003; Eckelman, 1997; Porter, 1981; Panshin and de Zeeuw, 1980).

The ANOVA tests revealed that patterns of radial variation of relative density$_{OD}$ and $_{12}$, density$_{12}$ and ring density were not significant at 95 percent confidence level, however, the values demonstrate a general pattern of radial decrease. A number of studies in ring porous hardwoods have demonstrated this trend (Burdon *et al.,* 2004; Fukazawa, 1984; Hamilton, 1961; Paul, 1930; Paul, 1960; Phelps and Chen, 1989; Springer and Olsen, 1987; Wheeler, 1987; Woodcock and Shier, 2002; Zhang *et al.,* 2004; Zobel and Sprague, 1998). Further studies suggest that a slight increase in density may occur towards the bark in more mature trees, however, this effect was not observed within the sample stems and may be attributed to the age of the sample trees (Panshin and de Zeeuw, 1980; Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998).

Montes *et al.,* (2007) explain a lack of significant radial variation by noting that radial density variation is less for denser hardwoods, such as black ash, than for less dense species. Woodcock and Shier (2002) and Pliura *et al.,* (2006) noted that young trees have wide variations in density, whereas older, mature trees utilized within this study tend to converge upon a sort of optimal density.

Most importantly, Zobel and Sprague (1998) attribute the absence of radial variation in hardwoods to the lack of significant difference between juvenile and mature wood. That is, many softwood species demonstrate wide variations in juvenile and mature wood densities. However, the literature suggests that many hardwoods contain more homogenous juvenile and mature wood zones with less distinct variation.

The trends in density variation found in ring porous woods can be further attributed to the decreasing amounts of latewood within the growth ring as the distance from the pith increases (Fukazawa, 1984; Wheeler, 1987; Woodcock and Shier, 2002). This is evident in the values of latewood percentages as noted below.

The ANOVA tests also revealed patterns of longitudinal variation to be not significant at 95 percent confidence, however, relative $density_{OD}$ and $_{12}$ and $density_{12}$ values followed a general pattern of increased values in the base, followed by a marginal decrease through the centre of the tree and increasing towards the top. This pattern has been noted in a number of hardwood species (Panshin and deZeeuw, 1980; Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998; Yanchuk *et al.,* 1983). However, the most common trend in longitudinal density is to display little variation and is reflected in the lack of variance between samples (Manwiller, 1979; Stringer and Olsen, 1987; Taylor 1979; Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998). As with radial variation, Zobel and Sprague (1998) attribute this trend to the lack of significant difference between juvenile and mature wood in hardwood species.

Modulus of Elasticity

Results of radial variance of MOE demonstrated a pattern of decreasing values from pith to bark, however, results proved to be non-significant at 95 percent confidence. These results are consistent with those provided by Hamilton (1961) and Clarke (1935). However, Zobel and van Buijtenen (1989) noted that every possible pattern of variation exists based on the species and measured property.

Longitudinal variation of MOE values displayed a consistent increase from stump to crown. These results are contradictory to the available literature, which suggests that butt sections are often superior in selected properties (Carmean and Boyce, 1974; Clarke, 1935; Clarke, 1938; Kraemer, 1956; Myer, 1930; Sterrett, 1917; Wilson, 1935). Jane (1956) and

Markwardt and Wilson (1935) further suggested that properties are lower in the butt sections from extremely wet sites. However, analyses of the mean values in the first longitudinal positions on each site provide no evidence of lower values in those positions.

Burdon *et al.,* (2004) noted results from this study are distinctive of the general features of wood from the base of the stem. That is, the area of the tree with the most rapidly changing properties. It is theorized that changes in properties occur rapidly in relation to excessive root swelling yet quickly become lessened as distance from the base increases (Burdon *et al.,* 2004; Zobel and van Buijtenen, 1989). Burdon *et al.,* (2004) suggest variation in properties is negligible past 3.5 metres. This trend is supported by post hoc test results from longitudinal variation of MOE which, demonstrates two subsets of positions; the first longitudinal position and longitudinal positions two through four.

<u>Modulus of Rupture</u>

Radial variance of MOR was not significant at 95 percent confidence and patterns of radial variation were negligible across all sites. This is contrary to literature provided by Hamilton (1961) and Clarke (1935) who found a radial decrease in properties. However, as discussed, Zobel and van Buijtenen (1989) noted that every possible pattern of variation exists based on the species and measured property. For example, Koehler (1933) found no relationship between toughness, a measure related to MOR, and radial position.

Longitudinal variance of MOR was not significant at 95 percent confidence and patterns of variation were negligible across all sites. As with MOE, these results are contradictory to research within the literature, which suggests that the butt logs are often superior in select properties (Carmean and Boyce, 1974; Clarke, 1935; Clarke, 1938; Kraemer, 1956; Myer, 1930; Sterrett, 1917; Wilson, 1935). However, as with MOE, no evidence can be found to support this trend in the measured properties. Further, Zobel and van Buijtenen (1989) noted that every possible pattern of variation exists and may be unique to the species.

Compression Parallel to the Grain

The ANOVA results demonstrated that radial variance of compression parallel to the grain was not significant at 95 percent confidence and patterns of radial variation were negligible across all sites. These results reflect patterns found in MOE and MOR variance and suggest that every possible pattern of variation exists based on the species and measured property (Zobel and van Buijtenen, 1989).

Longitudinal variation of compression parallel demonstrated a pattern of increasing compression values from stump to crown on all sites. These results are contradictory to research within the literature, which suggests that the butt logs are often superior in selected properties (Carmean and Boyce, 1974; Clarke, 1935; Clarke, 1938; Kraemer, 1956; Myer, 1930; Sterrett, 1917; Wilson, 1935). However, the results are consistent with Sterrett (1917) and Clarke (1935, 1938) both of whom suggested that the highest values in compression occur in the upper sections of the tree. Larger compression values in the upper sections of the tree suggest that the increased percentages of juvenile wood result in the increased values (Hamilton, 1961; Park *et al.,* 2009; Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998).

Janka Ball Side Hardness

Radial variance of side hardness was negligible across all sites and is in contrast to results by Hamilton (1961) indicating that hardness and toughness values were greatest at the pith and decreased towards the bark in *Quercus spp*. Further, Clarke (1935) and Sterrett (1917) have noted that the quality of wood decreases rapidly from pith to bark.

Longitudinal variation of side hardness displayed a consistent pattern of decreasing values from stump to crown on all sites. These results are consistent with Hamilton (1961) who noted that the highest values were found in the lower section of the stem. However, it was also suggested that wood equal in value to that of the base was also observed in the top sections of the stem, which was not observed in the present study. As noted previously, Zobel and van Buijtenen (1989) suggested that every possible pattern of variation exists based on the species and measured property.

Ring Width

Radial variance of ring width was non-significant across all sites and trends were not evident. Limited literature is available on ring width in ring porous hardwoods to support this trend; however, decreasing values in radial density suggest that ring width should be decreasing (Fukazawa, 1984; Guiher, 1965; Phelps and Workman, 1994; Zhang, 1995; Zobel and van Buijtenen, 1989). Further, testing of mechanical properties suggest that increased amounts of mature wood with lower latewood percentages contribute to lower mechanical property values

(Zhang, 1995). Although, the distinction between juvenile and mature wood noted in previous properties is not supported with this data.

Longitudinal variation of ring width demonstrated a pattern of increased ring widths in the first longitudinal positions followed by a rapid decrease in subsequent positions. This trend is most easily explained through examination of growth factors within trees. Ring width is known to vary based on the position of the ring in relation to the crown of the tree (Jozsa and Middleton, 1994; Larson, 1962; Wilson, 1984). Sampling stems based on merchantable height suggests that ring width will remain consistent through the upper longitudinal positions as these areas are unencumbered by branches, and the flow of resources is consistent. Increased ring widths in the lowest longitudinal positions could reflect the position in relation to large lateral roots (Fukazawa, 1984).

Latewood Percentage

The percentage of latewood decreased steadily from pith to bark and proved to be significant at 95 percent confidence. Limited literature is available on radial trends of latewood; however, this result is consistent with those demonstrated in relative density, density and ring density values (Burdon *et al.,* 2004; Fukazawa, 1984; Hamilton, 1961; Paul, 1930; Paul, 1960; Phelps and Chen, 1989; Springer and Olsen, 1987; Wheeler, 1987; Woodcock and Shier, 2002; Zhang *et al.,* 2004; Zobel and Sprague, 1998). Further, evidence from previous mechanical tests as well as patterns of growth in ring porous woods suggest that decreased amounts of latewood results in decreased properties (Zhang, 1995).

The trends in latewood percentage are not supported by results in radial ring width, as noted above. Ring width was found to be consistent across all radial positions and thus should not produce a significant change in latewood percentage. However, the literature is contradictory on the effects of environmental and genetic factors on the percentage of latewood. Zobel and van Buijtenen (1989) note that the percentage of latewood is under strong genetic control, while Savill and Kanowski (1993) suggest that environmental conditions largely determine the width of the latewood.

Several authors have noted that juvenile wood in ring porous species may lack the traditional ring porous structure and be composed almost entirely of fibers (Bowyer *et al.,* 2003; Clarke, 1930; Keith and Kellogg, 1981; Panshin and de Zeeuw, 1980; Tsoumis, 1991). It is also assumed within this study that the 'threshold method' utilized in X-ray densitometry analysis artificially inflates values of latewood nearer to the pith, while artificially lowering values closer to the bark.

Longitudinal variation of latewood percent demonstrated a consistent pattern of large values in the base, followed by a marginal decrease through the centre of the stem and increased values towards the top. This pattern closely resembles that of relative density, density and ring density values and has been noted in a number of species (Panshin and deZeeuw, 1980; Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998; Yanchuk *et al.,* 1983). These results are better supported by those demonstrated with ring widths; as larger widths were noted in the first longitudinal position followed by a rapid decrease. The increase in latewood percent noted in the top longitudinal position is best explained by the increase in juvenile wood and differing structure, as noted above.

LONGITUDINAL AND RADIAL VARIANCE IN JUVENILE CORE PROPERTIES

As noted, much of the available literature indicates that variation in both radial and longitudinal positions is altered by the presence of juvenile and mature wood. In hardwoods, the distinctions between juvenile and mature wood are minor and may not be accurate indicators of noted whole tree variation. It was hypothesised that examining the longitudinal trends of the juvenile core in the main stem would result in homogenous properties and no significant results. This was confirmed in results from the examined properties; MOE, compression parallel to the grain and side hardness.

Literature describing this trend in properties was not available and it is assumed that few researchers have examined properties in this manner, particularly in ring porous hardwoods. However, these results in combination with previous properties examined suggest juvenile wood is higher in density and thus related mechanical properties. Increased amounts of mature wood in the lower section of the stem are characterized by smaller ring widths, lower densities and lower strength properties and thus result in longitudinal variation in properties.

Several authors have noted that butt logs from extremely wet locations can have lower strength properties (Jane, 1956; Markwardt and Wilson, 1935). However, this trend was not observed and does not appear to significantly alter the effect of mature wood in the lower sections of the stem. Although, Burdon *et al.,* (2004) suggest that rapidly changing properties in the lower bole are characteristic of wood from the base of all trees and is a possible explanation for longitudinal variance.

PROPERTY VARIATION BETWEEN SITES

Results from all tests consistently demonstrated that properties displayed larger mean values on the second site, the upland site, or the third site, the well-drained site. The first site, the lowland swamp, consistently displayed inferior properties. These results were further demonstrated in post hoc test results, which indicated three distinct sites or two subsets, reflecting the wetland as compared to the more upland sites. These results are consistent with findings in a number of studies which suggest that growth and resulting properties of black ash are improved on drier sites as opposed to the wetland sites to which it is more commonly found (Benedict and Frelich, 2008; Carmean, 1979; Erdmann *et al.,* 2008; Hildebrandt, 1960; Howe, 1970; Keeland *et al.,* 1987; Larson, 1962; Paul, 1959; Savill and Kanowski, 1993; Schumann, 1973; Stewart and Krajicek, 1978; Tardiff and Bergeron, 1999; Zobel and van Buijtenen, 1989).

COMPARISON TO PUBLISHED VALUES

Comparison of calculated findings in the Thunder Bay seed zone with available literature from Jessome (1977) and Markwardt and Wilson (1935) demonstrate that properties are highly variable (Table 9). Mean values of relative density$_{12}$ varied from 13 percent larger on the wetland site, to 20 percent larger on the upland site. Mean values across all sites demonstrated a 17 and 18 percent increase over results published by Jessome (1977) and Markwardt and Wilson (1935), respectively. Relative density$_{OD}$ values followed a similar pattern and demonstrate a 14 and 16 percent increase over published values.

Values of MOE in the Thunder Bay seed zone varied considerably from those of published values, ranging from 49 percent lower on the first site, to 28 percent lower on the third site. Mean values for all samples, represent a 38 percent decrease over published values provided by Jessome (1977). When compared to Markwardt and Wilson (1935), mean values varied from 38 percent lower on the first site to 12 percent lower on the second site. Mean values for all samples represent a 24 percent decrease when compared to published values.

Values of MOR proved to be more consistent with published values, ranging from 8 percent lower on the first site to 15 higher on the third site. Mean values from the Thunder Bay seed zone represent a five percent increase over published values provided by Jessome (1977). Still more consistent results were found when compared to Markwardt and Wilson (1935), mean values varied from 11 percent lower on site one to 11 percent higher on site three. Mean values for all samples represent a negligible one percent increase.

Values of compression parallel to the grain proved to be consistent when compared to published values by both Jessome (1977) and Markwardt and Wilson (1935). Values represent a negligible difference over published values and ranged from 12 percent lower on site one to 12 percent higher on site two.

Side hardness values varied widely from published values and reflect a 23 percent increase on the first site to a 36 percent increase on the third site. Mean values from the Thunder Bay seed zone represent a 30 percent increase over published values provided by Jessome (1977). Still more variable values were shown when compared to Markwardt and Wilson (1935), ranging from 37 percent larger on the first site to 52 percent larger on the third site. Mean values represent a 46 percent increase over published.

There are a number of factors that could potentially account for the noted variation within measured properties. Alemdag (1984) and Singh (1986b) both noted differences in density values when compared to Jessome (1977) and attribute the variation to slightly different processing and calculation methods as well as geographic and climatic variation. Jessome (1977) sampled one site with six trees in Ontario while Markwardt and Wilson (1935) sampled two sites with five trees total in Michigan and Wisconsin. It is plausible that variations between the Thunder Bay seed zone and published values are a result of the noted variation of properties based on regional differences, climate and environmental factors (Alemdag, 1984; Hildebrandt, 1960; Koehler, 1933; Larson, 1962; Myer, 1930; Paul, 1963; Pliura *et al.,* 2006; Polge, 1973; Singh, 1986; Wiemann and Williamson, 2002; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989). Singh (1986a) suggests these variations provide evidence that regional sampling must supplement published values, as completed with this study.

RELATIVE DENSITY AND MECHANICAL PROPERTY RELATIONSHIP

Within this study, there appears to be a consistent, positive relationship between relative $density_{12}$ and the measured mechanical properties. A number of researchers have noted this trend on a per species basis (Bendtsen and Senft, 1986; Kretschmann, 2010; Zhang, 1995; Zhang, 1997, Zobel, 1984; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989). However, most studies have consistently accounted for more variation in the relationship between relative $density_{12}$ and selected properties then was observed (Bendtsen and Senft, 1986; Zobel and Talbert, 1984; Zobel and van Buijtenen, 1989). Within the softwood species, a greater level of correlation is noted when examining solely mature wood as opposed to juvenile wood (Zhang, 2003; Zobel, 1984). It is unclear if the more homogenous nature of hardwoods alters the relationship between relative density$_{12}$ and mechanical properties.

Further, Zhang (1995) concluded that a site-specific approach is required when predicting relationships, as the potential variability is too great. Silviculture and environmental factors can greatly affect growth rate, which in turn affects relative density and mechanical properties (Zhang, 1995). Kretschmann (2010) notes that relationships tend to vary around the average, ranging from 10 to 22 percent increase or decrease dependent on the species and measured property. However, results noted above provide evidence that mechanical properties vary with site conditions and may allow correlation or correction with relative density and property relationships.

CONCLUSION

The variation in mechanical properties at varying longitudinal and radial positions was investigated using small clear samples of wood from nine mature black ash stems grown in the Thunder Bay seed zone. Measured properties include relative density, density, MOE, MOR, compression parallel to the grain, Janka Ball side hardness and X-ray densitometry. It was hypothesized that differing longitudinal and radial positions would result in distinct variations in mechanical properties. It was also assumed that differing site characteristics would result in variations in properties.

The greatest level of variability was observed between sites in each of the selected properties. Results consistently displayed two subsets of sites; reflecting the second and third sites, or three distinct sites. Increased mechanical property values were identified in the upland and well-drained sites as compared to the lowland site. These results indicate that site conditions affect tree growth and development and subsequently mechanical properties. As noted, black ash is often considered a species associated with wet sites but these results suggest improved properties are found on more upland sites. Potential exists to develop black ash as a faster growing, more accessible hardwood species. In the future, research should focus on the relationship between specific sites and selected properties to further evidence of any correlation.

Radial variance was found to be not significant in all of the selected properties, reflecting a consistent and homogenous wood from pith to bark. The prevailing theories common to wood science reflect the idea that juvenile wood is severely detrimental to product quality (Adamopoulos *et al.,* 2007; Zobel, 1964; Zobel and van Buijtenen, 1989). However, the results presented in this thesis indicate a homogenous wood in the radial direction with less distinction between juvenile and mature wood.

Longitudinal variation was noted to be significant in properties including MOE, compression parallel to the grain, Janka Ball side hardness, ring width and latewood percentage. However, no significance was found in relative density, density, ring density or MOR. Much of this variation was also displayed in the first longitudinal position, an area of known variation. These results indicate that the wood of black ash is largely consistent, making it highly suited to various manufacturing and processing applications (Zobel, 1984). As Koga and Zhang (2004) note, variability in wood increases difficulty in processing and utilization.

Completion of 'property maps' in this study allows a more complete picture of mechanical properties and increases potential utilization allowing decision makers to better direct black ash to suitable applications (Clarke, 1935; Evans *et al.,* 2000; O'Keefe, 1972; Okkonen *et al.,* 1971; Park *et al.,* 2009; Van Buijtenen, 1969, Zobel, 1984). The Natural Resources Canada 'Value to Wood' program noted that allowing manufacturers the ability to purchase wood in 'bundles' of similar properties suited for similar applications would greatly enhance quality and competiveness (Lavoie *et al.,* 2006). For example, comparison of black ash values in this study with those of published values indicates that Janka Ball side hardness values are higher than associate species in the region and make it suitable for flooring applications. This is particularly true of higher sections in the stem.

This research has completed the most sample intensive analysis of black ash to date and provides a valuable addition to previous literature. Although results differ from those provided by Markwardt and Wilson (1935) and Jessome (1977), they can be explained through differences in location and sample intensity and together provide a more accurate picture of black ash properties. As noted throughout this thesis, there exists a gap in knowledge related to the properties and characteristics of black ash in Northwestern Ontario. The 'Value to Wood' program identified these gaps as fundamental barriers to utilization by manufacturers including flooring, window and doors, and architectural millwork (Lavoie *et al.,* 2006). Many species suitable for higher value products are underutilized due to a lack of knowledge (Hamilton, 1961; van Buijtenen, 1969). Further, Van Buijtenen (1969) argues that species volume is not an important factor in utilization, rather how suitable the species is to product development.

In the future, more effective utilization will require better management practices (Brazier, 1985; Cutter *et al.,* 2004; O'Keefe, 1972). This research has proven the consistent nature of mechanical properties in black ash, demonstrated the relationship between mechanical properties and site conditions and has provided evidence to support increased utilization. Forest managers in Northwestern Ontario must use this information to better manage black ash as a valuable forest commodity.

A number of limitations within the study were identified over the course of completing this thesis. For example, increasing the number of sample sites and including replicates of previous ecosites would provide a larger inference space with a more accurate representation of the effect of site on mechanical properties. Further, sample locations were limited to the Thunder Bay seed zone, a small area reflecting the northern limit of black ash growth. Sample trees also reflect a slight bias as these results replicate the highest quality material in mature trees, unaffected by serious internal and external defects and may not provide a complete representation of the resource. In terms of sample methodology, an additional longitudinal position is required to more accurately predict the level of variation from the first to the second longitudinal position. As noted, increased variation was found in the first longitudinal position; however, it is unclear as to the extent of variation with the first longitudinal position.

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APPENDIX I

MECHANICAL PROPERTY SUMMARY – SITE 1

Site	Tree	Longitudinal Position	Radial Position	D_{12} (Kg/m^3)	D_{OD} (Kg/m^3)	RD_{12}	MOR (Mpa)	MOE (Mpa)	Comp. Parallel (Mpa)	Side Hard. (N)	Ring Mean Density (kg/m3)	Ring Width (mm)	Ring LW (%)
1	1	0.25	1	591	554	526	78	6811	5085	37	368	1.55	39
1	1	0.25	2	591	554	526	78	6811	4976	37	521	1.05	39
1	1	0.25	3	583	541	519	78	6830	4503	36	654	1.05	59
1	1	0.50	1	562	525	499	54	5576	5085	32	660	0.88	67
1	1	0.50	2	561	524	501	56	6723	4976	32	577	0.87	42
1	1	0.50	3	561	527	501	73	7062	4503	36	577	0.87	42
1	1	0.75	1	580	548	517	61	5563	3330	28	437	0.95	40
1	1	0.75	2	561	528	500	58	5245	3972	32	368	1.06	40
1	1	0.75	3	561	528	500	58	5245	3972	32	438	1.04	40
1	1	1.00	1	565	559	504	62	6304	3330	27	546	0.96	46
1	1	1.00	2	571	531	508	64	5885	3972	29	502	1.01	46
1	1	1.00	3	571	531	508	64	5885	3972	29	462	1.07	41
1	2	0.25	1	670	636	596	90	7879	6208	38	703	0.99	59
1	2	0.25	2	641	607	572	86	6862	5753	36	608	1.08	35
1	2	0.25	3	610	572	544	80	6345	6320	34	588	1.55	43
1	2	0.50	1	614	579	550	87	7318	5670	37	666	0.95	41
1	2	0.50	2	624	591	559	85	7117	4948	37	595	1.05	35
1	2	0.50	3	624	591	559	85	7117	4948	37	595	1.05	35
1	2	0.75	1	635	601	565	81	6822	5253	39	724	1.04	58
1	2	0.75	2	616	580	549	78	6758	5130	38	577	0.95	28
1	2	0.75	3	616	580	549	78	6758	5130	38	577	0.95	28
1	2	1.00	1	612	570	545	75	5625	4553	37	665	0.78	59
1	2	1.00	2	606	565	540	70	5540	4553	33	535	1.20	29
1	2	1.00	3	606	565	540	70	5540	4553	33	535	1.20	29
1	3	0.25	1	703	657	625	91	7530	6075	42	636	0.83	60
1	3	0.25	2	710	666	630	90	7348	6240	41	622	1.31	61
1	3	0.25	3	710	666	630	90	7348	7065	41	610	1.62	61
1	3	0.50	1	659	632	585	83	7584	5070	37	623	0.88	52
1	3	0.50	2	674	639	599	87	8221	5555	38	592	0.93	50
1	3	0.50	3	674	639	599	87	8221	5555	38	542	0.96	43
1	3	0.75	1	650	634	582	80	7851	5515	40	697	0.74	52
1	3	0.75	2	673	634	600	82	7338	6060	41	712	1.24	52
1	3	0.75	3	673	634	600	82	7338	6060	44	712	1.24	52
1	3	1.00	1	698	663	621	84	8145	6225	45	654	1.05	59
1	3	1.00	2	681	660	610	84	8125	6225	45	521	1.05	39
1	3	1.00	3	681	660	610	84	8125	6225	45	521	1.05	39

APPENDIX II

MECHANICAL PROPERTY SUMMARY – SITE 2

Site	Tree	Longitudinal Position	Radial Position	D_{12} (Kg/m^3)	D_{OD} (Kg/m^3)	RD_{12}	MOR (Mpa)	MOE (Mpa)	Comp. Parallel (Mpa)	Side Hard. (N)	Ring Mean Density (kg/m3)	Ring Width (mm)	Ring LW (%)
2	1	0.25	1	627	590	557	80	6211	6228	37	742.2	1.54	64.3
2	1	0.25	2	614	576	546	82	6504	6195	39	771	1.40	63
2	1	0.25	3	614	576	546	82	6504	5883	39	771	1.40	63
2	1	0.50	1	626	596	559	100	11211	5945	47	639	1.36	80
2	1	0.50	2	648	633	591	94	8707	5223	53	474	1.09	48
2	1	0.50	3	628	602	561	101	9895	5223	55	474	1.09	48
2	1	0.75	1	639	612	576	95	9567	5570	50	521	2.18	58
2	1	0.75	2	608	577	546	86	7765	4320	47	505	1.32	48
2	1	0.75	3	608	577	546	86	7765	4320	47	505	1.32	48
2	1	1.00	1	628	601	565	83	8340	5570	48	711	1.52	77
2	1	1.00	2	628	601	565	83	8340	4320	48	579	1.24	54
2	1	1.00	3	628	601	565	83	8340	4320	48	579	1.24	54
2	2	0.25	1	679	632	603	70	5054	6375	38	456	1.52	60
2	2	0.25	2	658	605	585	76	5300	5680	37	495	1.52	75
2	2	0.25	3	593	596	536	71	4912	5025	35	546	2.16	71
2	2	0.50	1	687	666	612	92	8198	6043	45	449	0.97	43
2	2	0.50	2	636	603	569	84	7161	5606	42	510	1.50	53
2	2	0.50	3	636	603	569	84	7161	5606	42	588	1.48	77
2	2	0.75	1	675	607	603	91	9333	6120	45	606	1.66	75
2	2	0.75	2	624	604	558	86	7782	5017	43	556	1.55	58
2	2	0.75	3	624	604	558	86	7782	5017	43	487	0.92	41
2	2	1.00	1	662	602	592	98	10486	5210	45	649	1.80	95
2	2	1.00	2	624	604	559	88	8860	5021	44	675	1.80	85
2	2	1.00	3	624	604	559	88	8860	5021	44	634	1.18	54
2	3	0.25	1	689	643	614	88	8238	6943	44	728	1.99	66
2	3	0.25	2	673	646	600	89	8124	6469	43	707	2.39	67
2	3	0.25	3	685	635	613	88	7890	6200	46	626	1.44	30
2	3	0.50	1	702	671	624	96	11746	6350	48	744	2.05	83
2	3	0.50	2	696	667	622	100	9946	6320	49	688	1.54	61
2	3	0.50	3	696	667	622	100	9946	6320	49	649	0.72	54
2	3	0.75	1	726	701	649	99	11322	6363	52	745	1.63	68
2	3	0.75	2	720	692	644	92	10124	6487	49	714	1.43	54
2	3	0.75	3	720	692	644	92	10124	6487	49	768	1.00	54
2	3	1.00	1	745	735	670	105	11899	4897	62	742	1.54	64
2	3	1.00	2	753	723	676	120	13051	4897	61	771	1.40	63
2	3	1.00	3	753	723	676	120	13051	4897	61	771	1.40	63

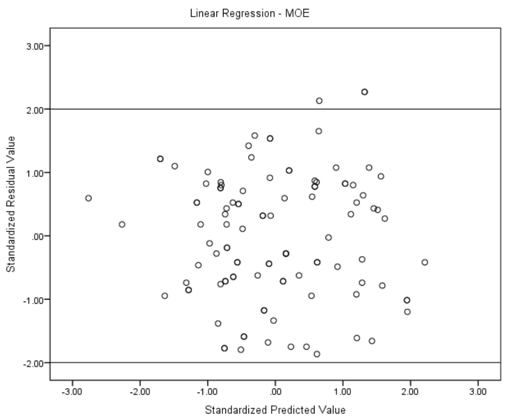
APPENDIX III

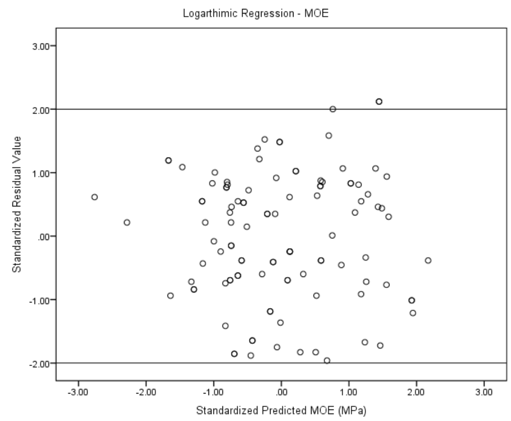
MECHANICAL PROPERTY SUMMARY – SITE 3

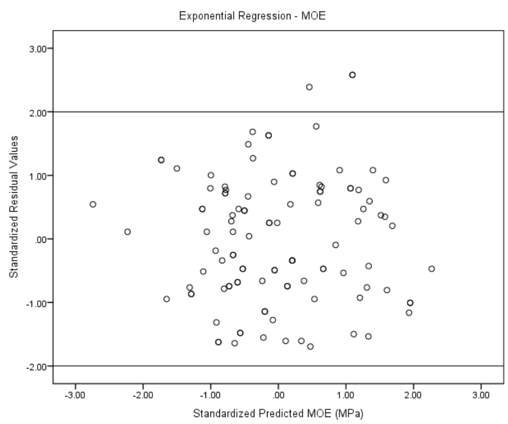
Site	Tree	Longitudinal Position	Radial Position	D_{12} (Kg/m^3)	D_{OD} (Kg/m^3)	RD_{12}	MOR (Mpa)	MOE (Mpa)	Comp. Parallel (Mpa)	Side Hard. (N)	Ring Mean Density (kg/m3)	Ring Width (mm)	Ring LW (%)
3	1	1.00	1	720	656	617	86	9392	5443	38	742	1.54	64
3	1	0.25	2	738	665	631	100	9366	6921	37	799	2.00	73
3	1	0.25	3	718	665	614	106	10330	6494	38	695	1.39	57
3	1	0.50	1	714	647	600	91	10828	5653	37	736	1.52	74
3	1	0.50	2	701	634	589	103	11146	6310	38	695	1.39	57
3	1	0.50	3	678	633	612	107	11074	5773	40	799	2.00	73
3	1	0.75	1	670	625	604	83	9963	4840	43	679	1.81	66
3	1	0.75	2	660	640	596	94	11094	5755	43	680	1.92	66
3	1	0.75	3	659	629	595	96	11153	5697	44	627	1.40	47
3	1	1.00	1	685	631	618	93	11843	6385	45	687	1.90	65
3	1	1.00	2	668	638	605	97	11104	5986	48	607	1.63	52
3	1	1.00	3	654	664	592	86	7741	5986	46	659	1.51	55
3	2	0.25	1	751	663	646	106	9844	6926	42	739	1.91	86
3	2	0.25	2	707	651	608	102	8560	6926	39	752	2.16	86
3	2	0.25	3	678	683	585	98	7017	6926	31	651	1.88	60
3	2	0.50	1	703	631	639	95	9520	6985	41	650	1.44	64
3	2	0.50	2	667	654	591	93	8535	6343	41	504	1.74	58
3	2	0.50	3	667	654	591	93	8535	6343	35	652	1.66	77
3	2	0.75	1	706	656	624	111	11026	6548	46	717	1.45	77
3	2	0.75	2	682	660	611	109	10211	6583	48	717	1.45	77
3	2	0.75	3	682	660	611	109	10211	6583	48	644	1.40	54
3	2	1.00	1	715	657	615	103	10318	5790	43	650	1.27	47
3	2	1.00	2	715	653	613	114	10928	5790	44	735	1.82	64
3	2	1.00	3	715	653	613	114	10928	5790	44	724	1.80	73
3	3	0.25	1	630	548	536	87	8115	3713	32	690	2.07	83
3	3	0.25	2	648	568	550	94	8221	4580	34	631	2.34	66
3	3	0.25	3	596	549	507	93	8324	5040	33	583	1.69	48
3	3	0.50	1	660	600	556	89	9223	4873	33	661	1.24	69
3	3	0.50	2	635	559	537	94	9123	5159	35	597	1.83	58
3	3	0.50	3	596	543	505	93	8600	5087	33	522	1.50	45
3	3	0.75	1	631	563	543	92	9850	4725	38	583	1.36	50
3	3	0.75	2	618	693	525	100	9913	5008	37	583	1.36	50
3	3	0.75	3	580	533	496	94	7156	5540	33	630	1.73	57
3	3	1.00	1	641	557	545	87	9463	4113	37	605	1.51	56
3	3	1.00	2	629	563	533	98	10119	4976	36	650	1.53	71
3	3	1.00	3	629	563	533	98	10119	4976	36	474	0.39	71

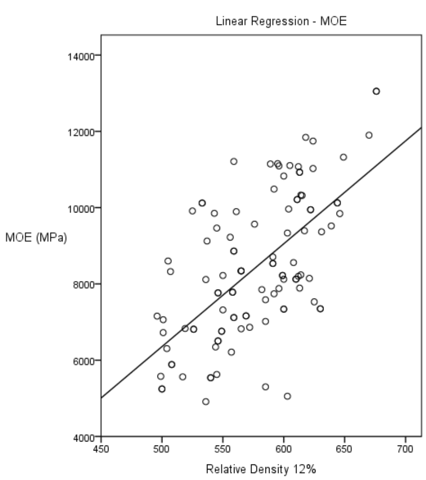
APPENDIX IV

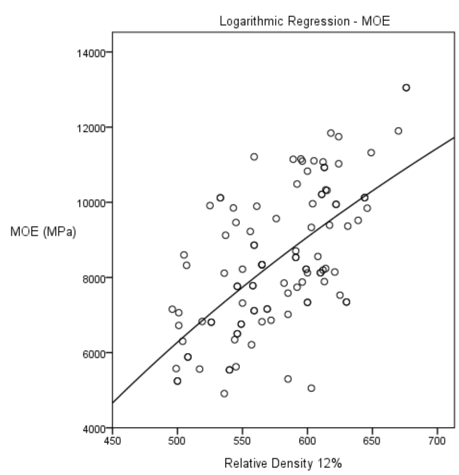
REGRESSION ANALYSIS OF MOE AND RELATIVE DENSITY

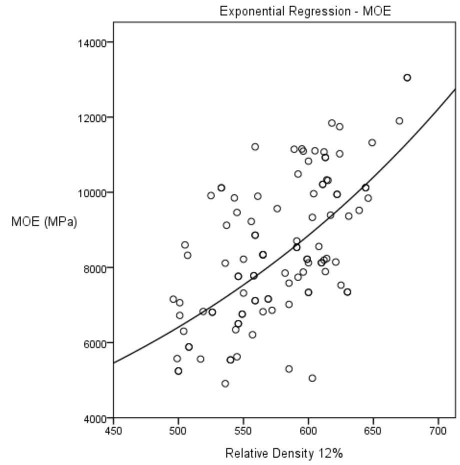

Linear Regression - MOE
Standardized Residual Value
Standardized Predicted Value
3.00
2.00
1.00
.00
-1.00
-2.00
-3.00
-2.00
-1.00
.00
1.00
2.00
3.00

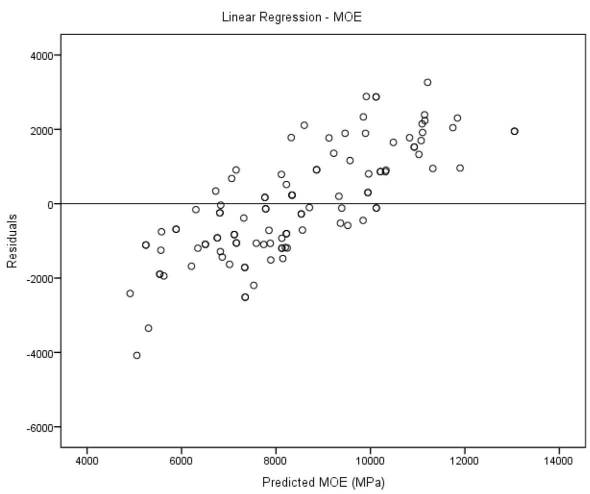

Logarthimic Regression - MOE
Standardized Residual Value
Standardized Predicted MOE (MPa)
3.00
2.00
1.00
.00
-1.00
-2.00
-3.00
-2.00
-1.00
.00
1.00
2.00
3.00

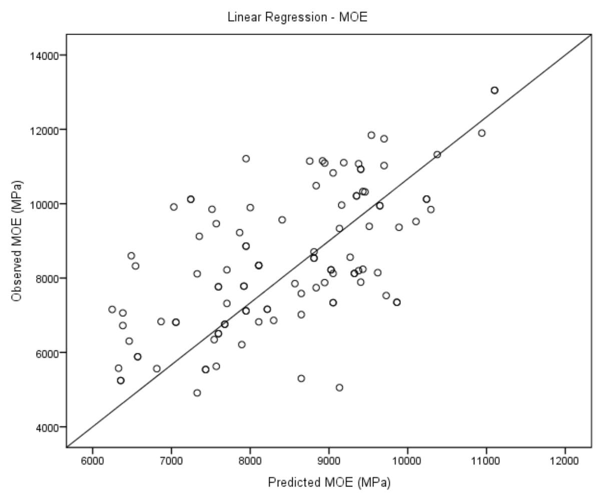

Exponential Regression - MOE
Standardized Residual Values
Standardized Predicted MOE (MPa)
3.00
2.00
1.00
.00
-1.00
-2.00
-3.00
-2.00
-1.00
.00
1.00
2.00
3.00

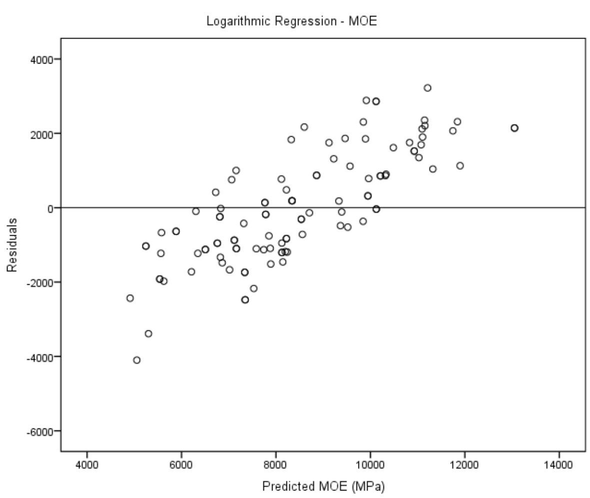

Linear Regression - MOE
MOE (MPa)
Relative Density 12%
14000
12000
10000
8000
6000
4000
450
500
550
600
650
700

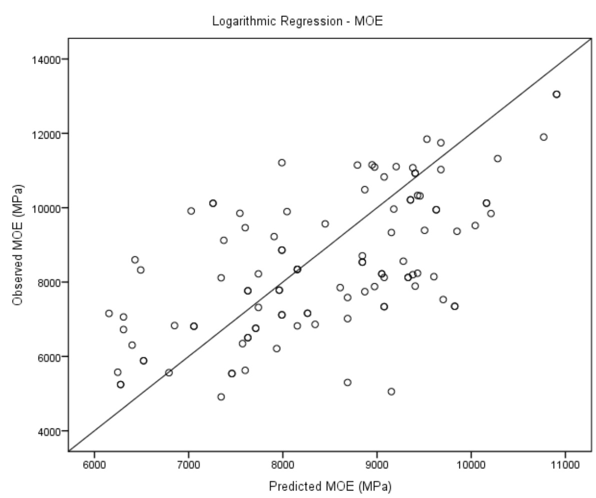

Logarithmic Regression - MOE
MOE (MPa)
Relative Density 12%
14000
12000
10000
8000
6000
4000
450
500
550
600
650
700

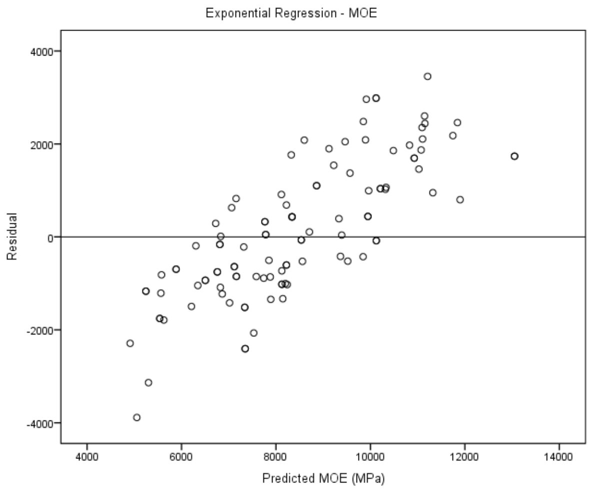

Exponential Regression - MOE
MOE (MPa)
Relative Density 12%
14000
12000
10000
8000
6000
4000
450
500
550
600
650
700

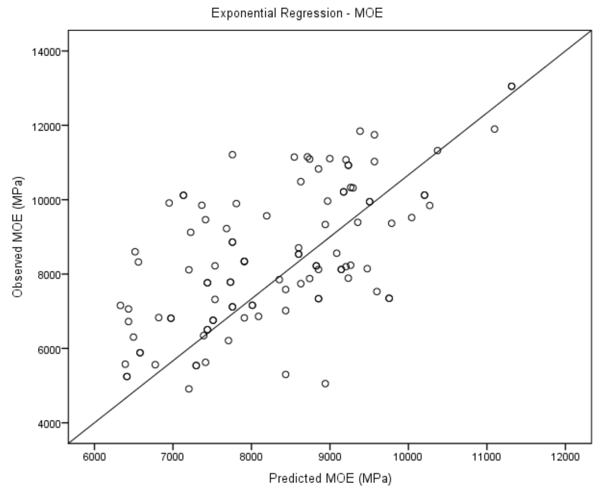

Linear Regression - MOE
Residuals
Predicted MOE (MPa)


Linear Regression - MOE
Observed MOE (MPa)
Predicted MOE (MPa)


Logarithmic Regression - MOE
Residuals
Predicted MOE (MPa)

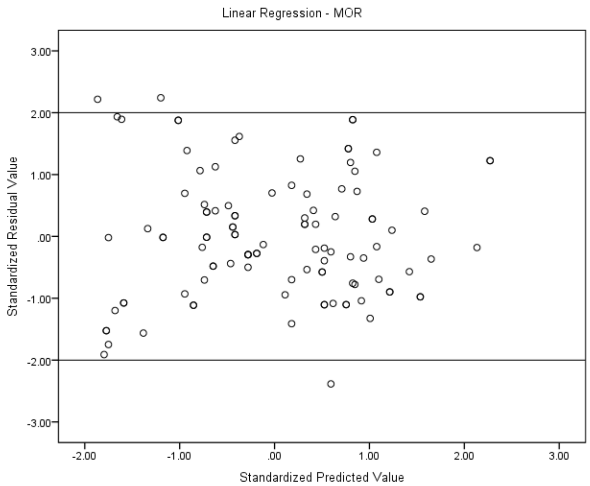

Logarithmic Regression - MOE
Observed MOE (MPa)
Predicted MOE (MPa)

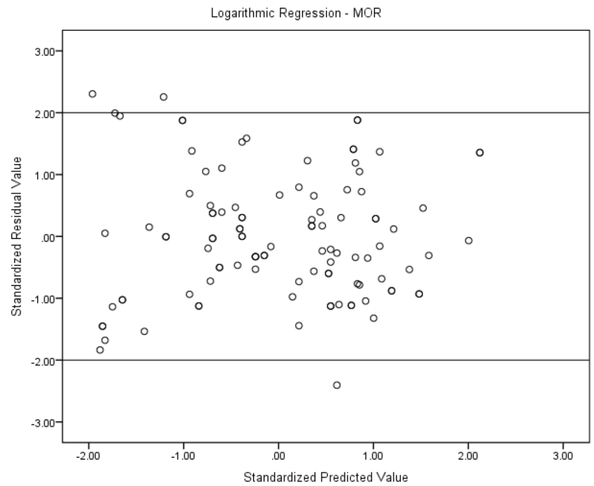

Exponential Regression - MOE
Residual
Predicted MOE (MPa)
4000
2000
0
-2000
-4000
4000
6000
8000
10000
12000
14000

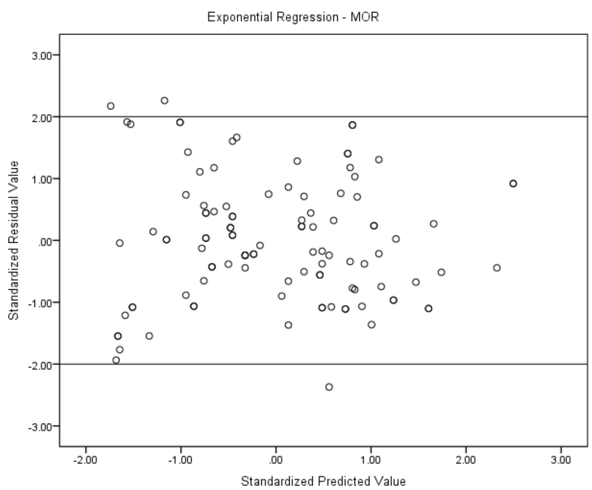

Exponential Regression - MOE
Observed MOE (MPa)
Predicted MOE (MPa)
14000
12000
10000
8000
6000
4000
6000
7000
8000
9000
10000
11000
12000

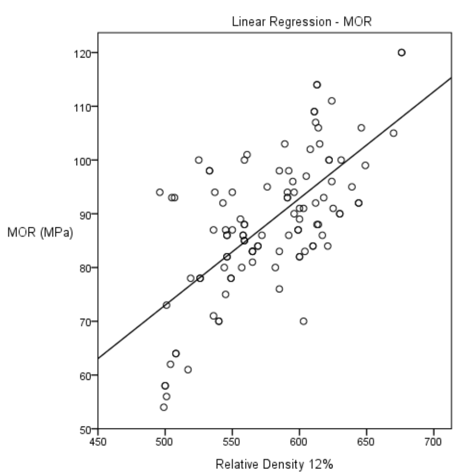
APPENDIX V

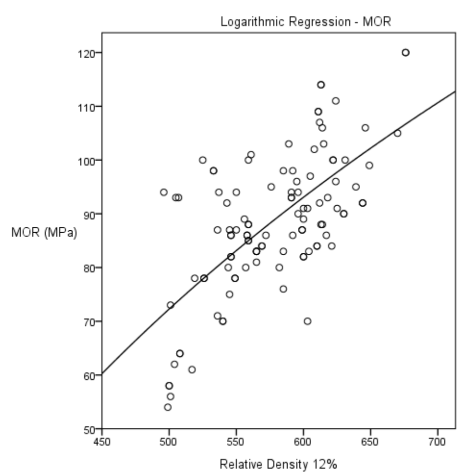
REGRESSION ANALYSIS OF MOR AND RELATIVE DENSITY

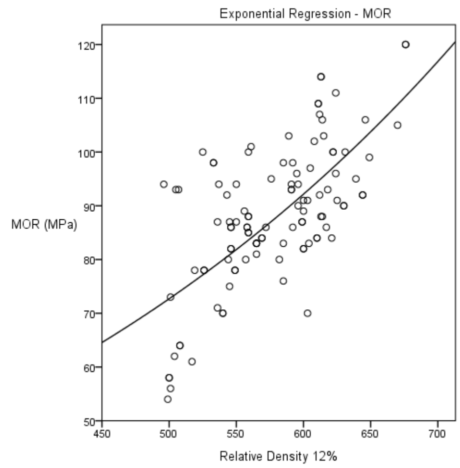

Linear Regression - MOR
Standardized Residual Value
Standardized Predicted Value

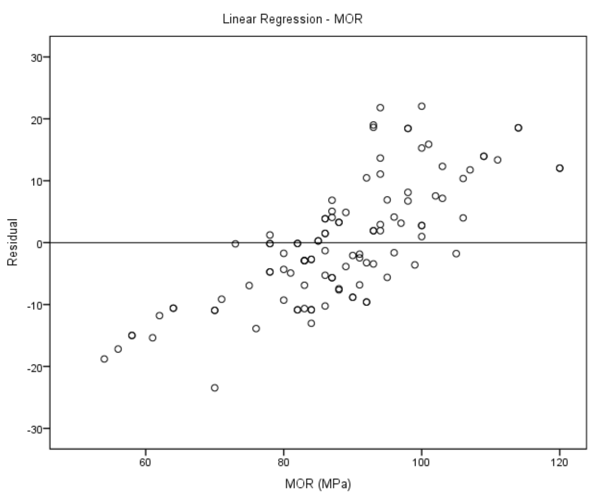

Logarithmic Regression - MOR
Standardized Residual Value
Standardized Predicted Value

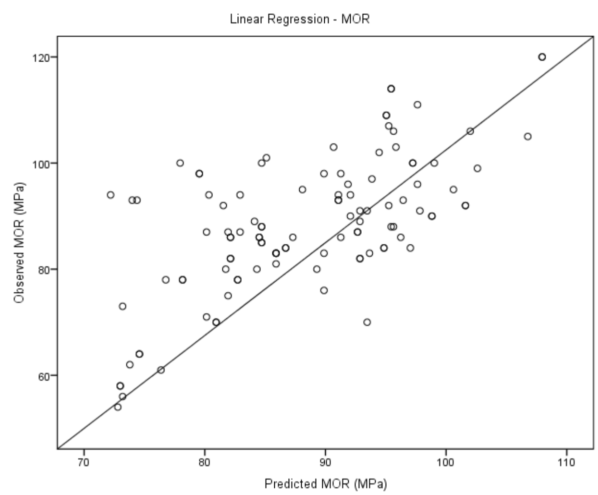

Exponential Regression - MOR
Standardized Residual Value
Standardized Predicted Value

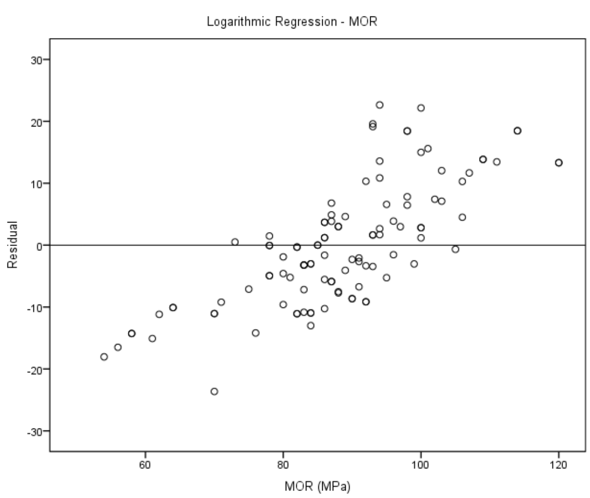

Linear Regression - MOR
MOR (MPa)
Relative Density 12%

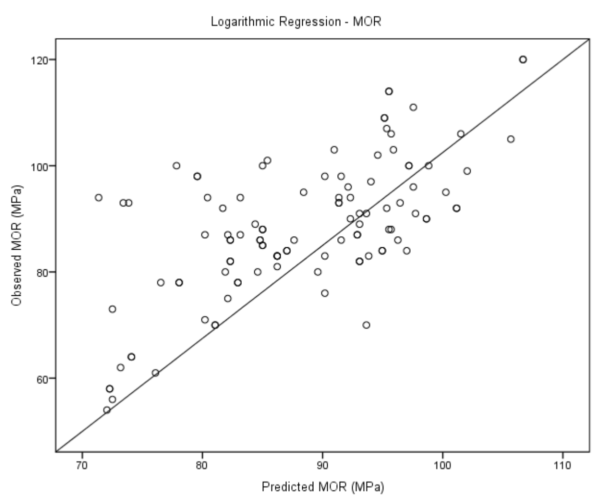

Logarithmic Regression - MOR
MOR (MPa)
Relative Density 12%

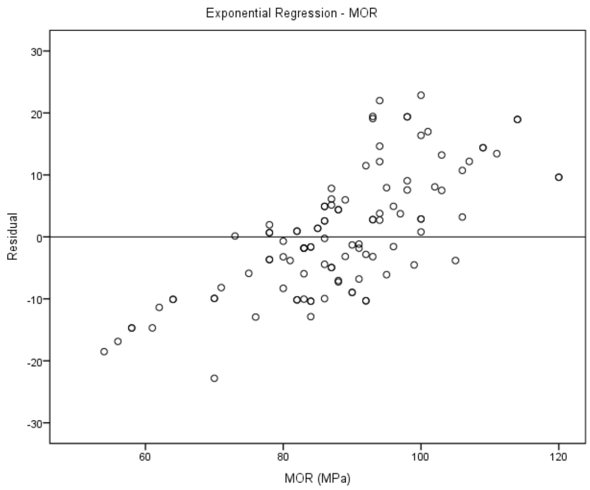

Exponential Regression - MOR
MOR (MPa)
Relative Density 12%
120
110
100
90
80
70
60
50
450
500
550
600
650
700

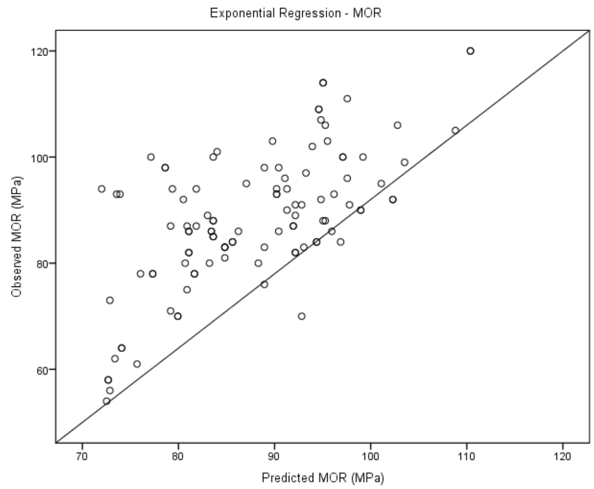

Linear Regression - MOR
Residual
MOR (MPa)
30
20
10
0
-10
-20
-30
60
80
100
120


Linear Regression - MOR
Observed MOR (MPa)
Predicted MOR (MPa)
120
100
80
60
70
80
90
100
110


Logarithmic Regression - MOR
Residual
MOR (MPa)
30
20
10
0
-10
-20
-30
60
80
100
120

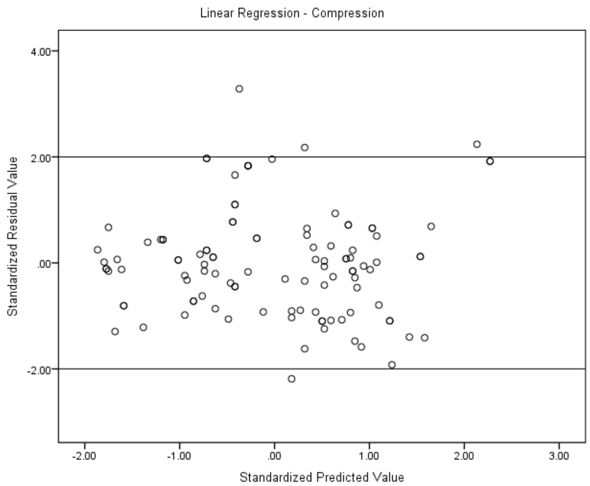

Logarithmic Regression - MOR
Observed MOR (MPa)
Predicted MOR (MPa)
120
100
80
60
70
80
90
100
110

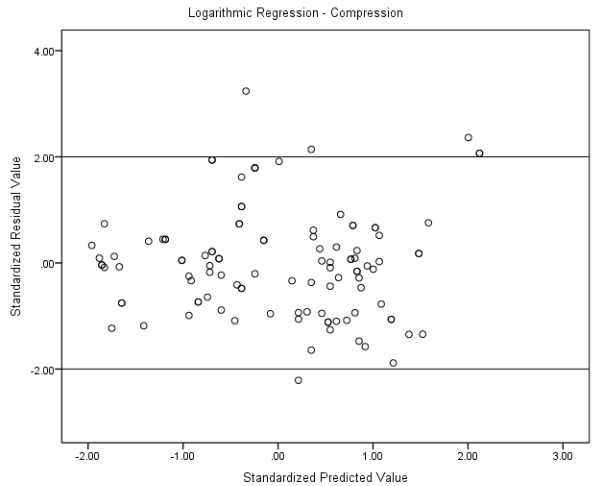

Exponential Regression - MOR
Residual
30
20
10
0
-10
-20
-30
60
80
100
120
MOR (MPa)

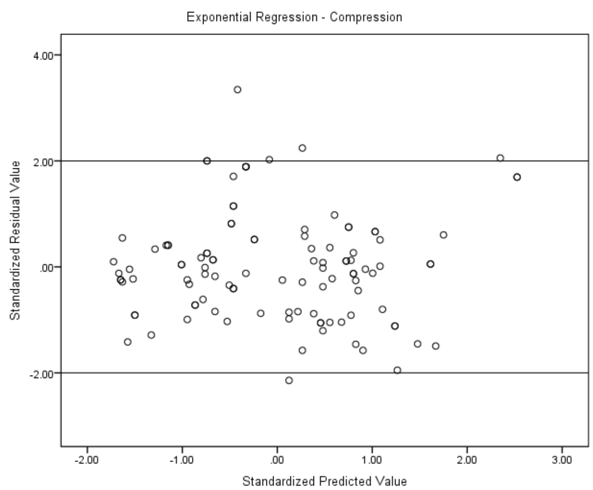

Exponential Regression - MOR
Observed MOR (MPa)
120
100
80
60
70
80
90
100
110
120
Predicted MOR (MPa)

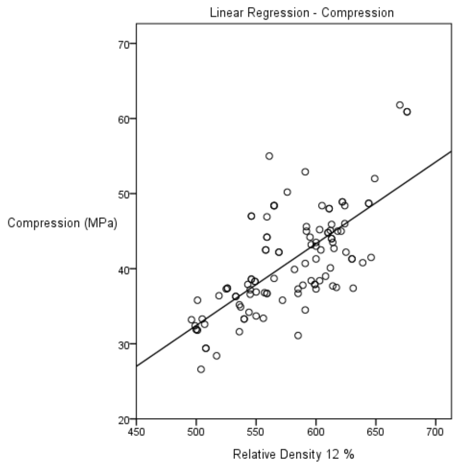
APPENDIX VI

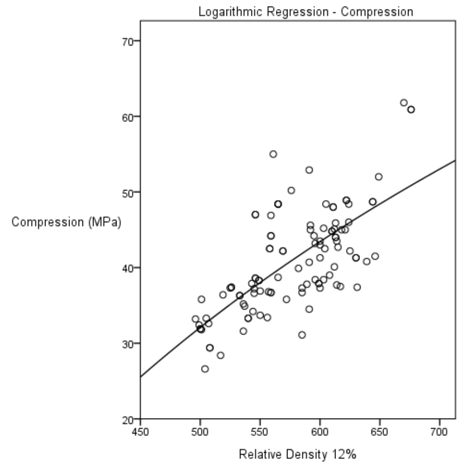
REGRESSION ANALYSIS OF COMPRESSION AND RELATIVE DENSITY

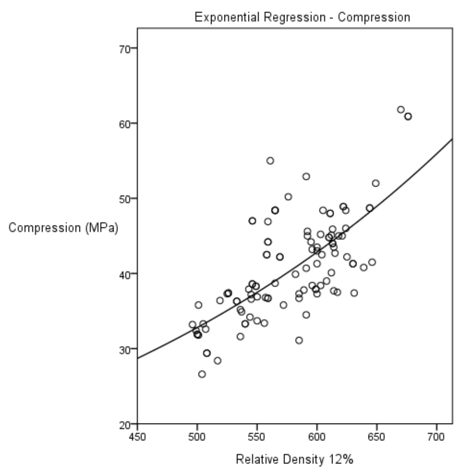

Linear Regression - Compression
Standardized Residual Value
Standardized Predicted Value
4.00
2.00
.00
-2.00
-2.00
-1.00
.00
1.00
2.00
3.00

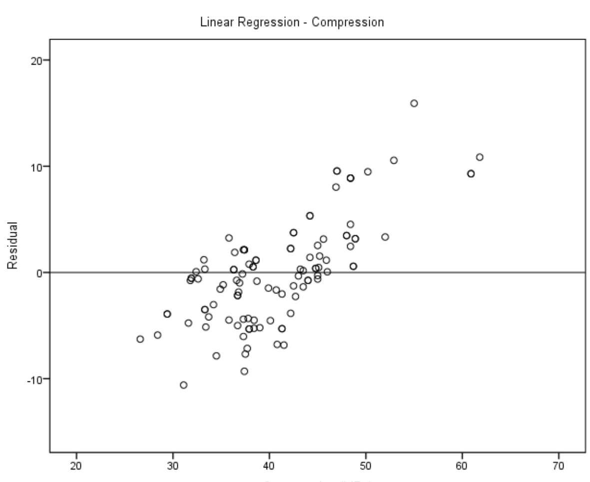

Logarithmic Regression - Compression
Standardized Residual Value
Standardized Predicted Value
4.00
2.00
.00
-2.00
-2.00
-1.00
.00
1.00
2.00
3.00

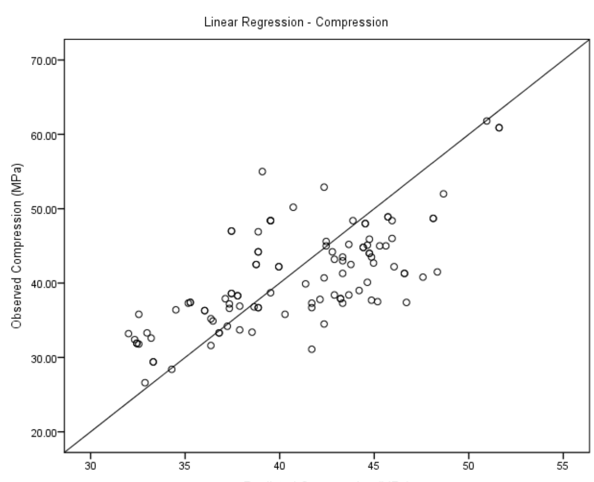

Exponential Regression - Compression
Standardized Residual Value
Standardized Predicted Value
4.00
2.00
.00
-2.00
-2.00
-1.00
.00
1.00
2.00
3.00

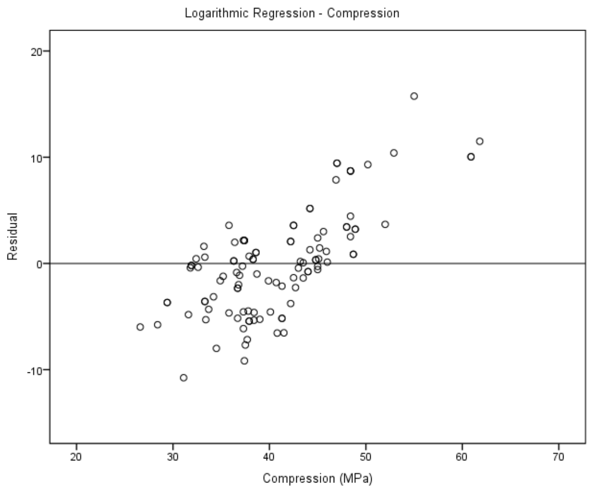

Linear Regression - Compression
Compression (MPa)
20
30
40
50
60
70
450
500
550
600
650
700
Relative Density 12 %

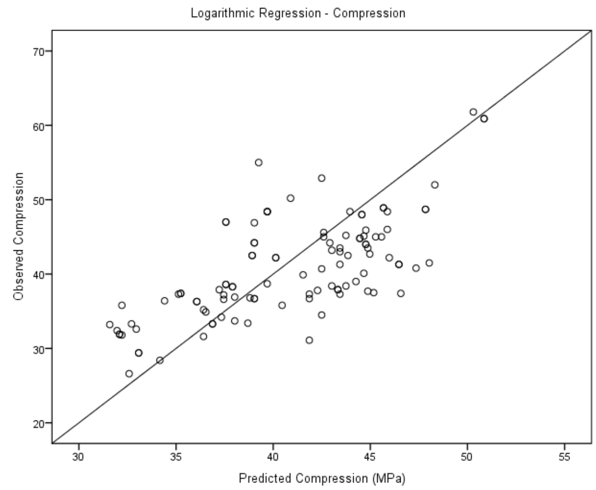

Logarithmic Regression - Compression
Compression (MPa)
20
30
40
50
60
70
450
500
550
600
650
700
Relative Density 12%

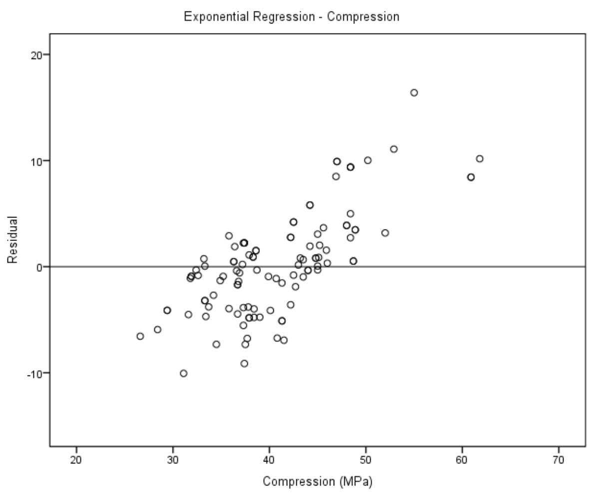

Exponential Regression - Compression
Compression (MPa)
20
30
40
50
60
70
450
500
550
600
650
700
Relative Density 12%

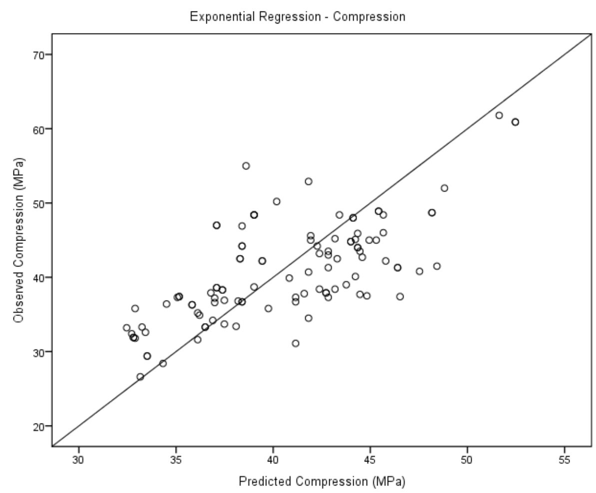

Linear Regression - Compression
Residual
20
10
0
-10
20
30
40
50
60
70
Compression (MPa)


Linear Regression - Compression
Observed Compression (MPa)
20.00
30.00
40.00
50.00
60.00
70.00
30
35
40
45
50
55
Predicted Compression (MPa)


Logarithmic Regression - Compression
Residual
Compression (MPa)
20
10
0
-10
20
30
40
50
60
70

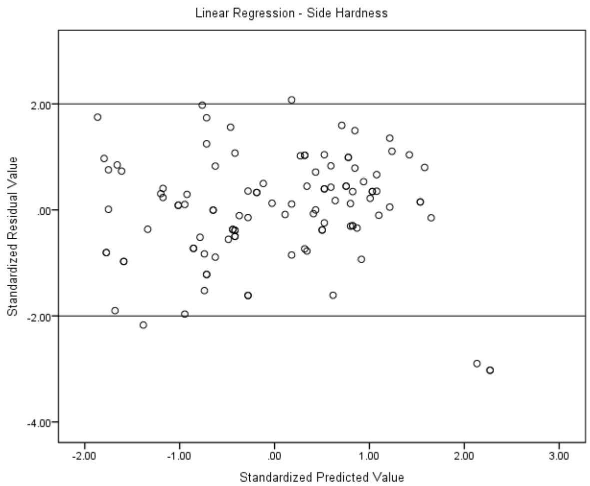

Logarithmic Regression - Compression
Observed Compression
Predicted Compression (MPa)
70
60
50
40
30
20
30
35
40
45
50
55

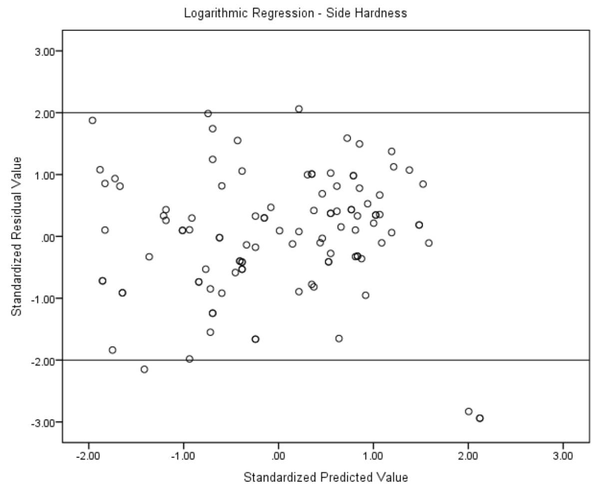

Exponential Regression - Compression
Residual
Compression (MPa)
20
10
0
-10
20
30
40
50
60
70

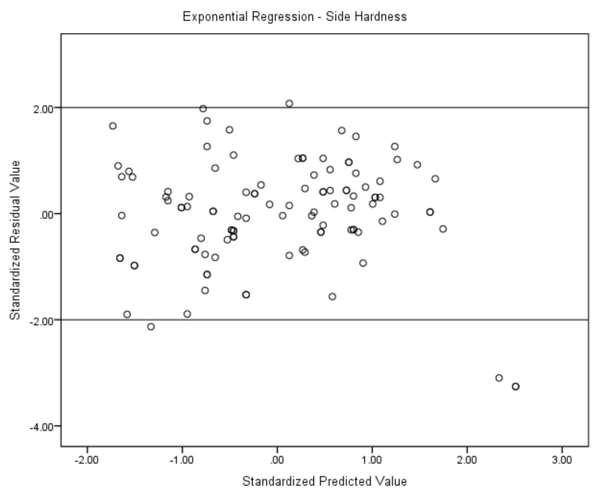

Exponential Regression - Compression
Observed Compression (MPa)
Predicted Compression (MPa)
70
60
50
40
30
20
30
35
40
45
50
55

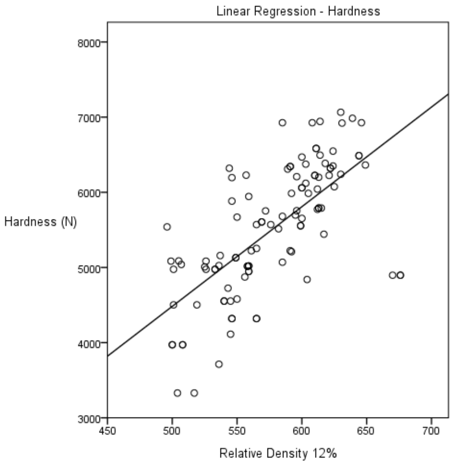
APPENDIX VII

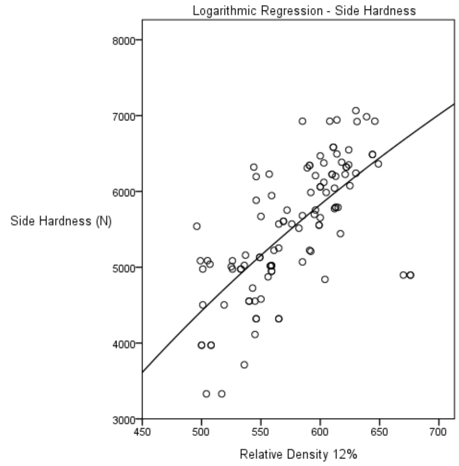
REGRESSION ANALYSIS OF SIDE HARDNESS AND RELATIVE DENSITY

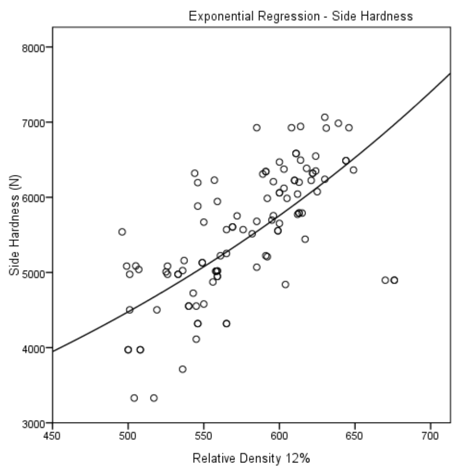

Linear Regression - Side Hardness
Standardized Residual Value
2.00
.00
-2.00
-4.00
-2.00
-1.00
.00
1.00
2.00
3.00
Standardized Predicted Value

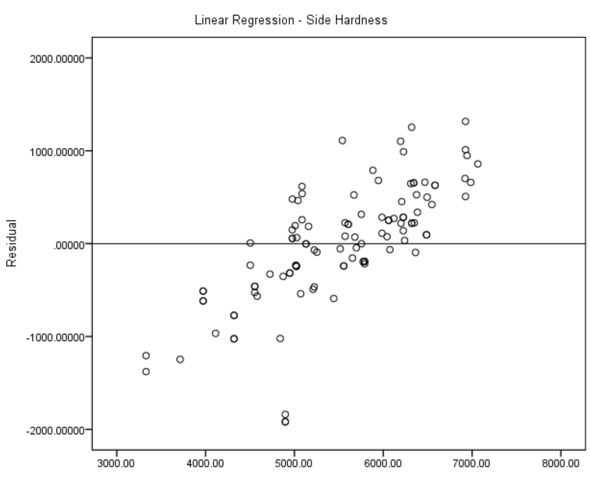

Logarithmic Regression - Side Hardness
Standardized Residual Value
3.00
2.00
1.00
.00
-1.00
-2.00
-3.00
-2.00
-1.00
.00
1.00
2.00
3.00
Standardized Predicted Value

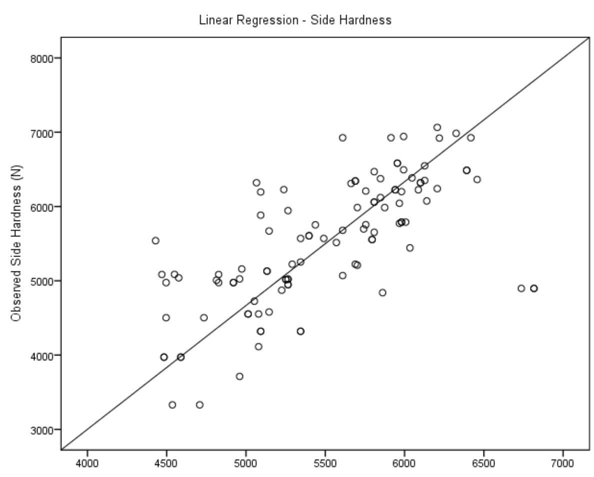

Exponential Regression - Side Hardness
Standardized Residual Value
2.00
.00
-2.00
-4.00
-2.00
-1.00
.00
1.00
2.00
3.00
Standardized Predicted Value

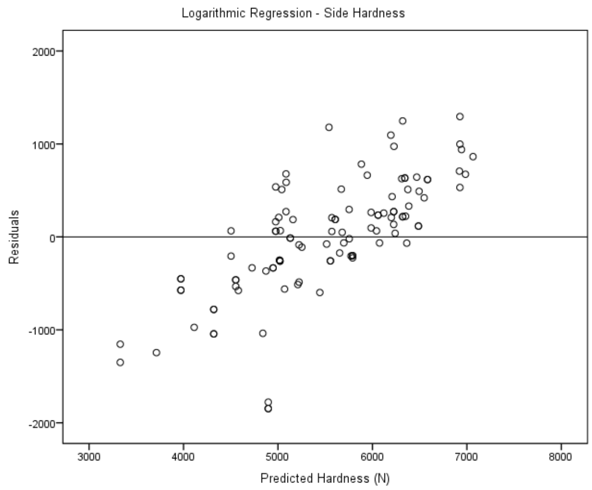

Linear Regression - Hardness
Hardness (N)
8000
7000
6000
5000
4000
3000
450
500
550
600
650
700
Relative Density 12%

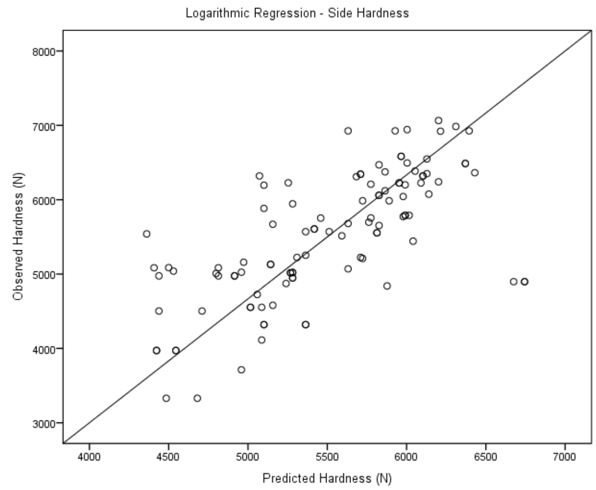

Logarithmic Regression - Side Hardness
Side Hardness (N)
8000
7000
6000
5000
4000
3000
450
500
550
600
650
700
Relative Density 12%

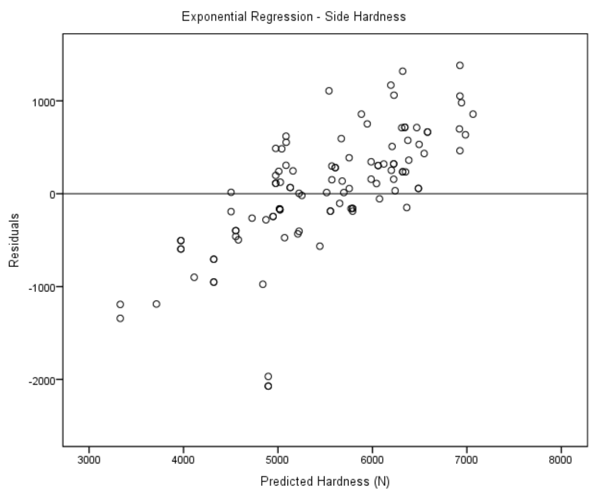

Exponential Regression - Side Hardness
Side Hardness (N)
8000
7000
6000
5000
4000
3000
450
500
550
600
650
700
Relative Density 12%

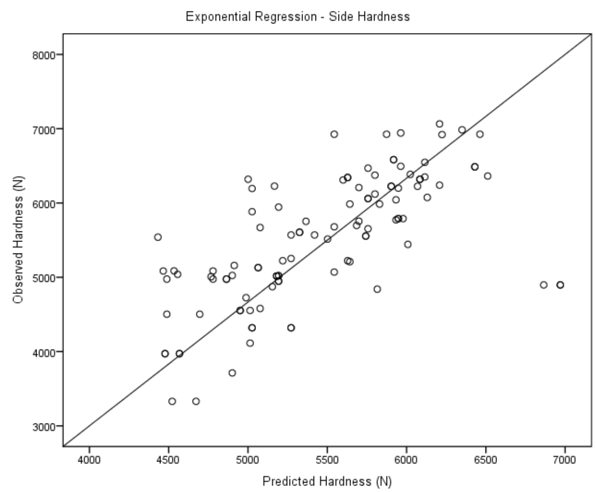

Linear Regression - Side Hardness
Residual
2000.00000
1000.00000
.00000
-1000.00000
-2000.00000
3000.00
4000.00
5000.00
6000.00
7000.00
8000.00
Side Hardness (N)


Linear Regression - Side Hardness
Observed Side Hardness (N)
8000
7000
6000
5000
4000
3000
4000
4500
5000
5500
6000
6500
7000
Predicted Hardness (N)


Logarithmic Regression - Side Hardness
Residuals
Predicted Hardness (N)


Logarithmic Regression - Side Hardness
Observed Hardness (N)
Predicted Hardness (N)


Exponential Regression - Side Hardness
Residuals
Predicted Hardness (N)


Exponential Regression - Side Hardness
Observed Hardness (N)
Predicted Hardness (N)